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RECONNAISSANCE OF THE COAL-BED METHANE RESOURCES IN PENNSYLVANIA

Antonette K. Markowski

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RECONNAISSANCE OF THE COAL-BED METHANE RESOURCES IN PENNSYLVANIA

by Antonette K. Markowski
Bureau of Topographic and Geologic Survey

PENNSYLVANIA GEOLOGICAL SURVEY

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RECONNAISSANCE OF THE COAL-BED METHANE RESOURCES IN PENNSYLVANIA

by
Antonette K. Markowski

ABSTRACT

Once considered a dangerous, undesirable waste product by underground miners in Pennsylvania and worldwide due to its potentially explosive nature, coal-bed methane has been overlooked and misunderstood as a resource. Methane from coal is an abundant natural gas in Pennsylvania. From an environmental standpoint, methane comprises 18 percent of the world's major greenhouse gases and is second only to carbon dioxide in its contribution to global warming, yet it has 20 to 30 times the heat-trapping capacity of carbon dioxide. As an emerging energy source, coal-bed methane rivals conventional natural gas in composition and heating value and lacks nuisance gases such as carbon monoxide (found occasionally in trace amounts), nitrogen oxides, and sulfur compounds. As a gas reservoir, a coal bed is superior to a conventional gas sandstone because it can hold 2 to 7 times as much gas, due to the large internal surface area of coal and the very tight packing of methane molecules.

The purpose of this study was to evaluate and identify the coal-bed methane resource potential of the major coal seams in Pennsylvania to determine how much might be available for use as a resource. The study area included the Main Bituminous field in the southwestern part of Pennsylvania and the Anthracite region of the northeastern part of the state.

Methane is the primary component of natural gas and is the simplest and most stable hydrocarbon. Its formation is a natural part of the carbon cycle. It originates in coal beds and is retained until coal-bed methane production, mining, or natural migration occurs. The gas can be adsorbed on the internal surfaces of the coal or within its molecular structure; it can be trapped within the matrix porosity; it can exist as free gas within fractures; or it can be dissolved in water that is present in the coal.

Major geologic factors and reservoir characteristics to be considered in determining the feasibility of coal-bed methane development are the following: (1) coal rank and quality; (2) thickness of overburden and depth of the coal; (3) coal-bed thickness; (4) structural setting; (5) coal porosity (influences diffusion characteristics and storage capacity); (6) coal fracture permeability (influences drainage radius); (7) permeability of adjacent strata (traps); (8) gas and water content of the coal; and (9) hydrostatic pressure and pressure/stress relationships of the coal reservoir (hydrogeologic regime).

Coal-bed methane exists in Pennsylvania because of the presence of Pennsylvanian-age rocks and an abundance of coal. Several formations accumulated when conditions were right for coal formation; these conditions included the presence of swamps and alluvial plains. Long periods of plant growth and accumulation of the plant remains, followed by compaction and heating, contributed to the formation of thick beds of coal. The Pottsville Formation, the Allegheny Formation, the Conemaugh Group, the Monongahela Group, and the Dunkard Group are the important bedrock units in the Bituminous region for coal-bed methane. In the Anthracite region, the important units are the Pottsville and Llewellyn Formations, which are probably time-equivalent to the Allegheny Formation in southwestern Pennsylvania.

Twenty-seven coal-bed methane pools in western Pennsylvania were recognized during routine processing of well records as of August 2000. There are 228 wells that have been documented, most of which are within these pools. It is estimated that 125 wells are producing methane. The pools, fields, and associated wells reflect historical, serendipitous, and current coal-bed methane well completions from 1938 to 1998.

This report features a compilation of new data and previously published data from federal research during the 1970s and 1980s in Pennsylvania for a reconnaissance of coal-bed methane resources. Two sets of data obtained from 455 coal-bed samples from the bituminous coal fields were analyzed. The data indicate that gas content increases with increasing depth and rank.

The first data set is from 62 coal samples from 15 coal beds. Thirty of these samples were obtained and tested by the Pennsylvania Geologi-

cal Survey for gas content and gas composition from six exploratory drill holes in the Main Bituminous field of Armstrong, Cambria, Greene, and Somerset Counties. The other 32 samples of the first data set and their gas content results were provided directly by industry for Fayette, Greene, and Westmoreland Counties. Coal chemical data are available for 47 of the 62 samples. Total gas contents were determined for the 30 new coal samples using the former U.S. Bureau of Mines direct method of testing. Results from the direct method can be used for resource evaluation and recoverability of the methane or for ventilation specifications by multiplying the total coal tonnage estimated for a given area by the methane content per ton of coal.

Graphs of depth and thickness of coal, respectively, versus total gas content are provided for the first data set. Gas contents ranged from 10 cubic feet per ton for the Upper Kittanning seam in Armstrong County to 395 cubic feet per ton for the Lower Freeport seam in Cambria County. Desorbed gas values for the Pennsylvania Geological Survey tested samples were corrected to standard temperature and pressure. Additional graphs were generated to determine relationships between (1) depth and thickness, respectively, versus total gas content, taking into consideration the influence of coal rank and roof lithology, and (2) elapsed time and cumulative gas. Depth and gas content are directly related based on this and previous studies. However, there is no positive correlation between coal thickness and gas content.

Gas chromatography analyses were obtained for 60 samples from 15 coal beds. Methane accounted for 90 percent or more of the gas from each coal sample after the gas sample was corrected to an air-free basis. Low methane values, however, indicate a shallow coal and/or a loss of methane and the introduction of nitrogen to the sample over time. In addition to methane, hydrocarbon gases of higher molecular weight were detected in the gas samples, including ethane, propane, butane, and pentane. The relative amounts of these components appeared to increase over time.

Heating values were determined for the gas and coal samples. Average values for coal-bed methane were approximately 1,000 British thermal units per standard cubic foot, comparable to those of natural gas. Extremely low heating values were obtained for coal-bed methane from above-drainage (above the water table or potentiometric surface), shallow coal beds (less than 500 feet) that were also close to mining operations. In general, coal-bed methane appears to be a viable substitute for natural gas due to its high calorific value and absence of sulfur compounds and carbon monoxide. Heating values on a dry, ash-free basis for the bituminous coal samples tested for coal-bed methane ranged from 14,602 to 15,557 British thermal units.

The second, or compilation, data set includes gas contents from all 455 coal samples—393 from the former U.S. Bureau of Mines, the U.S. Department of Energy, and the Methane Recovery from Coalbeds Project, and the 62 samples of the first data set (provided by industry and the Pennsylvania Geological Survey). The 393 samples were obtained from 31 bituminous coal beds in Allegheny, Armstrong, Greene, Indiana, Washington, and Westmoreland Counties, and nine anthracite coal beds in Lackawanna and Schuylkill Counties. Based on 21 bituminous and three anthracite seams, reported gas contents were greater than or equal to 125 cubic feet per ton from depths of 340 feet in the Uniontown coal of Washington County to 1,417 feet in the Freeport coal (name as reported) of Greene County. Gas contents of three bituminous and three anthracite seams ranging in depth from 575 feet in the Lower Kittanning coal of Indiana County to 1,060 feet in the Lower Kittanning coal of Westmoreland County were greater than or equal to 300 cubic feet per ton.

According to the results of petrographic and chemical analyses from other studies, coals that exhibit the highest total gas contents based on values ranging from 35 to 339 cubic feet per ton are, in descending stratigraphic order, the following: Waynesburg, Uniontown, Pittsburgh, Brush Creek, Mahoning, Upper Freeport, Upper Kittanning, Middle Kittanning, Brookville, and Mercer. These results are based on total vitrinite percent and mean-maximum reflectance percent. The Pittsburgh seam, although significantly mined out today, still accounts for more than 60 percent of the bituminous coal production from Pennsylvania and is a prime target for coal-bed methane because of its continuity, thickness, and high gas content. Other Pennsylvania coal beds, although not as thick as the Pittsburgh, can produce desirable results when production is combined from stimulating multiple thin coals.

Overall estimates for the Northern Appalachian coal basin are 61 trillion cubic feet of gas-in-place, and the estimated resource of coal-bed methane for southwestern Pennsylvania and northwestern West Virginia is 51 trillion cubic feet of gas-in-place, based on a 1988 topical report for the Gas Research Institute by Kelafant and others. The technically recoverable coal-bed methane resources for the basin are projected at 11.48 trillion cubic feet from the U.S. Geological Survey oil and gas resource assessment of 1995. The total recoverable coal-bed methane resources (including those from anthracite) in Pennsylvania are estimated at 2,654 billion cubic feet in a 1983 report by Geomega, Inc.

Most of the available information for Pennsylvania is based on the minable coals. An attempt should be made in future coal-bed methane studies in Pennsylvania to better define the coal-bed methane resource from deeper, currently unminable coal beds. Some additional exploration data could be obtained from existing core-hole logs and/or geophysical logs from oil and gas wells drilled in the deeper coal-bearing parts of the Northern Appalachian coal basin. Ultimately, coring to obtain gas contents of these coal beds should be performed to better quantify the coal-bed methane resource for Pennsylvania and the Northern Appalachian coal basin.

INTRODUCTION

PURPOSE AND SCOPE

Objectives of Study

The objective of this preliminary report is to identify and evaluate the natural gas resource potential of the major coal seams in Pennsylvania. This includes the generation, compilation, and assessment of new and existing coal-bed methane (CBM) data. It is hoped that the information in this report will be of value to the oil and gas industry, the coal industry, public utilities, and consulting firms interested in the impact of this burgeoning industry. The report is also directed to those companies interested in exploration and development of the CBM resources in southwestern Pennsylvania; to state, county, and local government agencies that wish to attract this industry; and to the general public, who should be aware that a CBM resource exists in this time of global economic uncertainty.

Assuming that the resource potential is good, additional objectives include (1) identification of key areas that have a high CBM content; (2) correlation of gas contents with the stratigraphy of various coal beds, their thicknesses, ranks, and behavior of the gas with time; and (3) assessment of the implications of exploiting CBM as a supplemental and/or alternative energy source for the Commonwealth.

Location of Study Area

The study area includes much of the Main Bituminous field (within the central part of the Northern Appalachian coal basin in the Appalachian Plateaus province) in the southwestern part of Pennsylvania and the outlying Anthracite region (Ridge and Valley province and part of the Appalachian Plateaus province) of the northeastern part of the state (Figures 1 and 2; Table 1; Figures 3 and 4). The map in Figure 3 also illustrates the distribution and rank of coals in the state. This report is focused on coals from the Main Bituminous field because more data are available. The Anthracite region is discussed in the "Selected Previous Studies in Pennsylvania" section on page 15 and the "Eastern Pennsylvania" section on page 37. No CBM data are available for the Broad Top, Georges Creek, and North-Central fields (Figure 3).

General Geologic Setting and Stratigraphic Distribution in the Northern Appalachian Coal Basin

Extending from central and eastern New York to central Alabama, the Appalachian coal basin includes a portion of the Appalachian Plateaus province. The length of this basin is about 806 miles (Lyons, 1986). The study area is within the northern part of the Appalachian coal basin. Paleozoic rocks in and around the area have been deformed into long, gentle open folds as represented by the fold axes in Figure 5. The orogeny that formed these folds, the Alleghanian, occurred after the Pennsylvanian and before the Late Triassic-Early Jurassic rifting in eastern North America. Fractures and faults, the presence or absence of which is so important in the transmission and storage of fluids in coal beds, formed before, during, and after the main phase of Alleghanian folding.

The data in this report concern coals from the Pennsylvanian-Permian Dunkard Group down through the Lower Pennsylvanian Pottsville Formation. The information indicates the presence of very gassy coals in certain parts of the Northern Appalachian coal basin that deserve serious consideration. Most of this gas occurs at depths of less than 3,000 feet in the Northern Appalachian coal basin and less than 6,000 feet throughout the United States (Petroleum Information Corporation, 1986).

Number and Kind of Samples

A compilation of CBM gas-content data from two data sets involves a total of 455 coal-bed samples. The first data set includes gas contents for 62 coal sam-

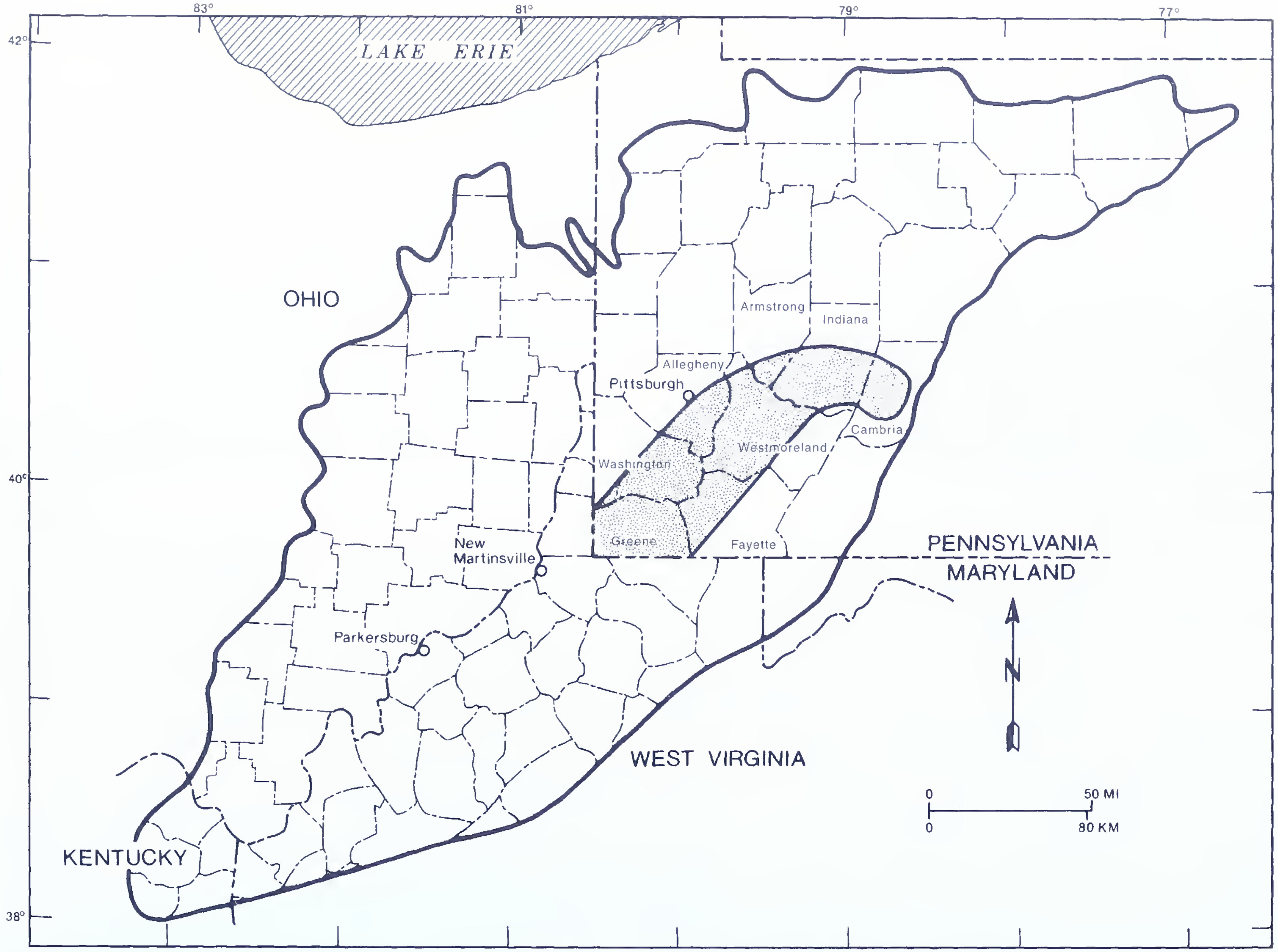

Figure 1. Map of the Northern Appalachian coal basin showing the Main Bituminous field part of the study area (stippled) and county boundaries (modified from Adams and others, 1982).

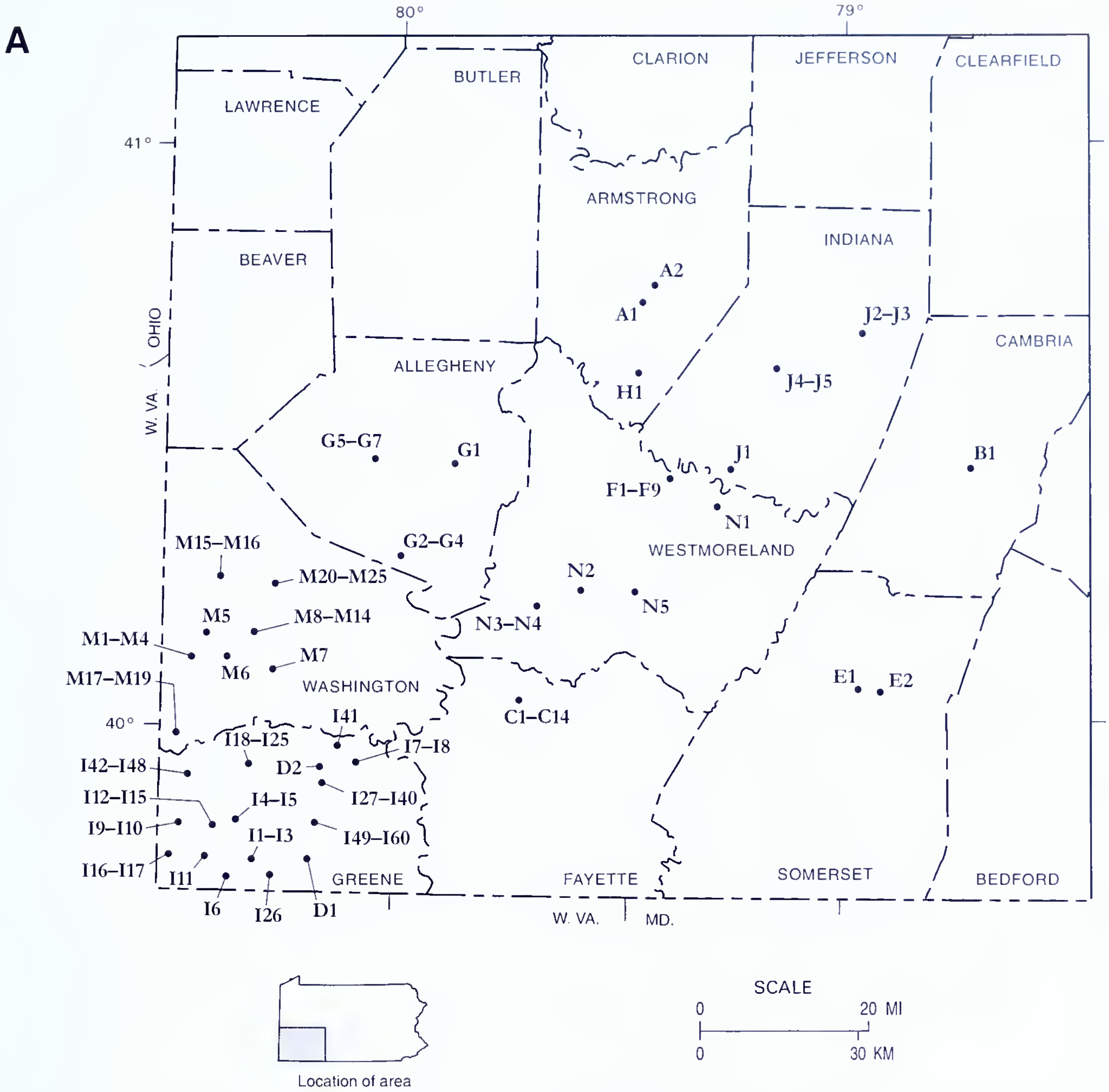

Figure 2. Location maps of coal-bed methane test drill holes and sampling sites for the study area. There may be more than one drill hole or sampling site at a location; these are indicated by a range of numbers. Table 1 shows more specific information for each drill hole and sampling site. A. Southwestern Pennsylvania. B. Northeastern Pennsylvania.

ples from 15 different coal beds. These data were obtained directly from field testing of exploratory coal cores by the Pennsylvania Geological Survey and compiled from industry data sheets. Thirty core samples from 10 coal beds were tested for gas content and coal chemistry (Appendix 1), and gas composition and heating values (Appendix 2) were obtained from six exploratory drill holes in the Main Bituminous field of Armstrong, Cambria, Greene, and Somerset Counties (Figure 6). The total gas content versus depth and thickness, respectively, for each coal bed, and elapsed time versus cumulative gas, are displayed in the graphs of Appendix 3. The Pennsylvania Geological Survey used the direct method of testing employed by the former U.S. Bureau of Mines (USBM) to determine total gas contents. Supplemental gas-content information, previously generated, was provided by industry for Fayette, Greene, and Westmoreland Counties; 32 samples from 10 coal beds were tested. The total gas content versus depth and thickness, respectively, for each coal bed are displayed in the graphs of Appendix 3.

The second data set includes gas contents from a compilation of 455 samples: 393 from the USBM, the U.S. Department of Energy (USDOE), and the Methane Recovery from Coalbeds Project (MRCP); and 62 samples from industry and the Pennsylvania

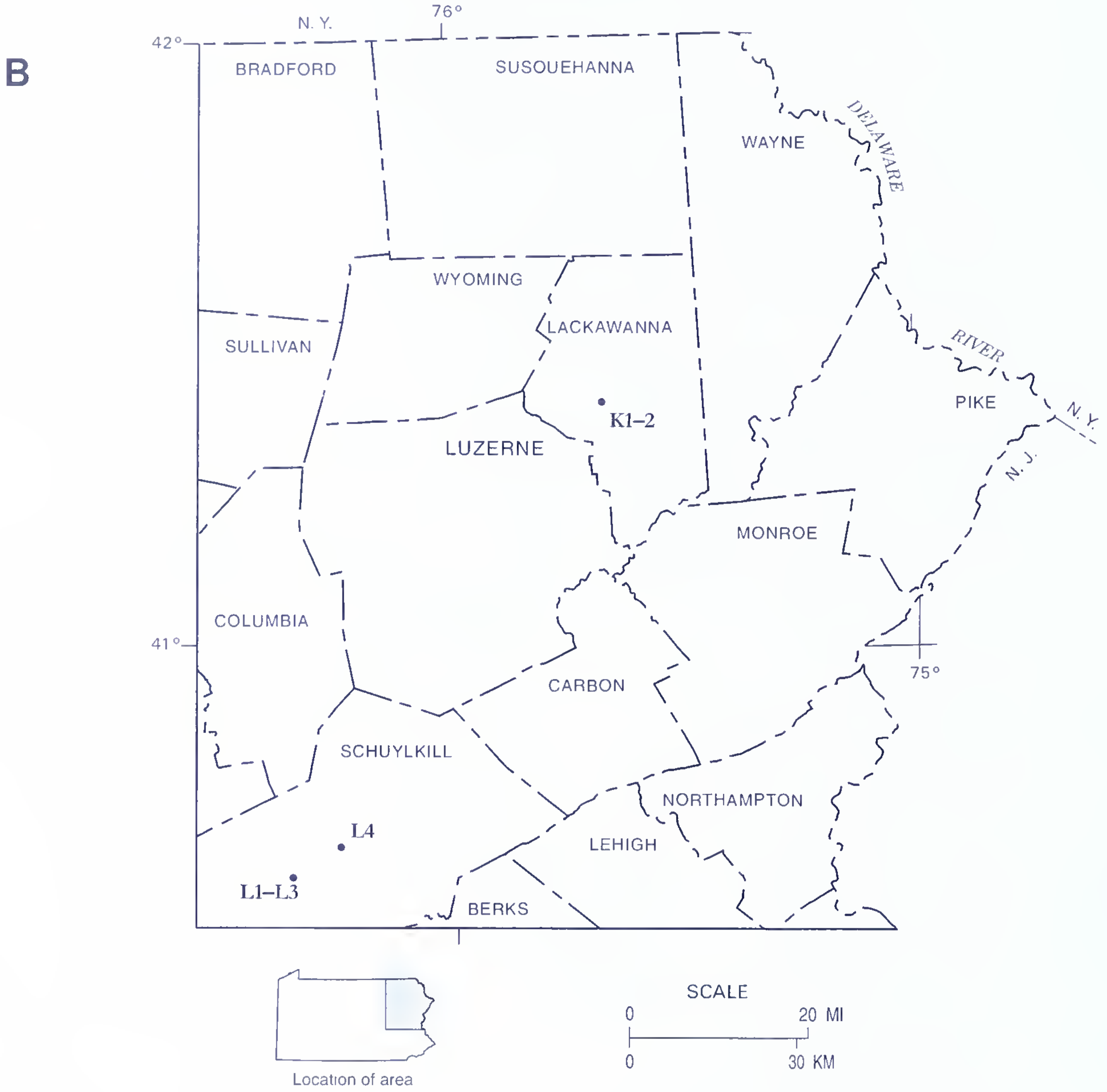

Figure 2. *(Continued)*.

Geological Survey as discussed above. The 393 samples were obtained from 40 bituminous and anthracite coal beds in Allegheny, Armstrong, Greene, Indiana, Lackawanna, Schuylkill, Washington, and Westmoreland Counties. Both data sets were compiled for graphical analysis of depth and thickness, respectively, versus total gas content when the influence of rank only is considered (Appendix 4), and when rank and roof lithology are considered (Appendix 5).

Limitations of Study

Although this report includes the Northern and Southern Anthracite fields of the northeastern part of the state, the primary focus is on the Main Bituminous field of southwestern Pennsylvania because more data are available there. The description of coals as "economic" or "commercial" in this report pertains to CBM production unless specified for mining.

Time Involved in Data Collection

Data collection for this study took approximately two years and included the purchase and construction of PVC canisters having individual valve assemblies, sampling coal cores from exploration drilling, and completing the desorption process. This process must be continued until a very low emission rate (about 10 cc/g/day [cubic centimeters per gram per day], or 320 cf/t/day [cubic feet per ton per day], for a week) is attained (Diamond and Levine, 1981). About a year was used to measure the gas from the cores; this was possible because the Pennsylvania Geological Survey was able to keep the coal for research purposes.

HISTORY OF COAL-BED METHANE

Long known as a bane to the mining community, the reputation of CBM as an accessible energy source has been largely overlooked and misunderstood. Through-

Table 1. *Specific Information for Locations of Test Drill Holes and Sampling Sites Shown in Figure 2*

Test drill hole or sampling site[1]	County	Township	Quadrangle	Coal bed	Depth to base of coal bed (feet)
A1	Armstrong	Kittanning	Whitesburg	Upper Kittanning	275
				Lower Kittanning	419
A2	do.	do.	do.	Upper Kittanning	132
				Lower Kittanning	257
B1	Cambria	Cambria	Ebensburg	Upper Freeport	724
				Lower Freeport	771
C1	Fayette	Dunbar-Perry	Dawson	Lower Kittanning	333
C2	do.	do.	do.	do.	417
C3	do.	do.	do.	do.	473
				Brookville	547
C4	do.	do.	do.	Lower Kittanning	618
				Brookville	695
C5	do.	do.	do.	Lower Kittanning	738
C6	do.	do.	do.	do.	791
C7	do.	do.	do.	do.	801
C8	do.	do.	do.	do.	845
				Clarion	878
C9	do.	do.	do.	Lower Kittanning	856
C10	do.	do.	do.	do.	996
C11	do.	do.	do.	Clarion	380
C12	do.	do.	do.	do.	445
C13	do.	do.	do.	do.	1,090
C14	do.	do.	do.	Brookville	1,270
D1	Greene	Wayne	Oak Forest	Waynesburg "A"	510
				Waynesburg	594
				Sewickley	840
				Redstone	888
				Pittsburgh rider	913
				Pittsburgh	934
D2	do.	Washington	Waynesburg	Ten Mile	351
				Little Washington	610
				Waynesburg "A"	660
				Waynesburg	730
				Sewickley	938
E1	Somerset	Stonycreek	Stoystown	Middle Kittanning	108
				Lower Kittanning	145
E2	do.	do.	do.	Middle Kittanning	75
				Lower Kittanning	108
F1	Westmoreland	Derry	Blairsville-Saltsburg	Upper Freeport	627
F2	do.	do.	do.	do.	708
F3	do.	do.	do.	do.	716
F4	do.	do.	do.	do.	639
F5	do.	do.	do.	do.	598
F6	do.	do.	do.	do.	646
F7	do.	do.	do.	do.	720
F8	do.	do.	do.	do.	607
F9	do.	do.	do.	do.	609
G1	Allegheny	Penn Hills	Braddock	do.	494
G2	do.	Jefferson	Glassport	Freeport	695
				Middle Kittanning	801
				Clarion	970
				Brookville	1,020
				Mercer	1,110
G3	do.	do.	do.	Upper Kittanning	834
G4	do.	do.	do.	do.	834
G5	do.	—	—	Upper Freeport	595
G6	do.	—	—	Upper Kittanning	834

Table 1. *(Continued)*

Test drill hole or sampling site[1]	County	Township	Quadrangle	Coal bed	Depth to base of coal bed (feet)
G7	Allegheny	—	—	Mahoning	703
H1	Armstrong	Kiskiminetas	Avonmore	Lower Kittanning	327
I1	Greene	Gilmore	Holbrook	Waynesburg	489
I2	do.	do.	do.	Upper Waynesburg	580
				Lower Waynesburg	586
I3	do.	do.	do.	Upper Waynesburg	681
				Lower Waynesburg	686
I4	do.	Jackson	do.	Pittsburgh	859
I5	do.	do.	do.	Waynesburg	948
I6	do.	Gilmore	Hundred	Upper Waynesburg	558
				Lower Waynesburg	563
I7	do.	Morgan	Mather	Upper Freeport	1,072
I8	do.	—	do.	do.	937
I9	do.	Aleppo	New Freeport	Waynesburg	974
				Sewickley	1,181
				Pittsburgh	1,280
I10	do.	do.	do.	Sewickley	961
I11	do.	Freeport	do.	do.	859
I12	do.	Jackson	do.	Pittsburgh rider	827
				Pittsburgh	839
I13	do.	do.	do.	do.	906
I14	do.	do.	do.	Sewickley	773
I15	do.	do.	do.	Waynesburg	618
I16	do.	Springhill	do.	do.	458
				Sewickley	669
				Pittsburgh	786
I17	do.	—	do.	do.	1,184
I18	do.	—	Rogersville	Fish Creek	150
				Jollytown	193
				Washington A	417
				Washington	465
				Waynesburg "B"	501
				Waynesburg "A"	556
				Upper Waynesburg	615
				Lower Waynesburg	619
I19	do.	—	do.	Fish Creek	213
				Ten Mile	266
				Washington	558
				Upper Waynesburg	696
				Lower Waynesburg	700
				Sewickley	899
I20	do.	—	do.	do.	794
I21	do.	—	do.	Ten Mile	180
				Upper Washington	457
				Washington	486
				Waynesburg "A"	547
				Upper Waynesburg	598
				Lower Waynesburg	601
				Uniontown	672
I22	do.	—	do.	Washington A	506
				Washington	552
				Upper Waynesburg	695
				Lower Waynesburg	698
				Uniontown	762
I23	do.	—	do.	Washington	632
I24	do.	—	do.	do.	682

Table 1. *(Continued)*

Test drill hole or sampling site[1]	County	Township	Quadrangle	Coal bed	Depth to base of coal bed (feet)
125	Greene	—	Rogersville	Upper Washington	412
				Waynesburg "A"	710
				Upper Waynesburg	820
				Lower Waynesburg	823
126	do.	Wayne	Wadestown	Upper Waynesburg	673
				Lower Waynesburg	678
127	do.	Franklin	Waynesburg	Waynesburg	158
				Sewickley	378
				Pittsburgh rider	489
				Pittsburgh	497
				Bakerstown	897
128	do.	do.	do.	Upper Freeport	1,091
				Upper Kittanning	1,194
				Middle Kittanning	1,243
				Clarion	1,301
				Mercer	1,409
129	do.	do.	do.	Upper Freeport	1,036
130	do.	do.	do.	do.	1,058
131	do.	do.	do.	do.	1,307
132	do.	do.	do.	Pittsburgh	582
133	do.	do.	do.	do.	593
134	do.	do.	do.	do.	612
135	do.	do.	do.	do.	626
136	do.	do.	do.	do.	666
137	do.	do.	do.	do.	705
138	do.	do.	do.	do.	720
139	do.	do.	do.	Washington	69
				Waynesburg rider	429
				Waynesburg	434
				Sewickley	646
				Pittsburgh rider	748
				Pittsburgh	755
140	do.	do.	do.	do.	778
141	do.	Morgan	Waynesburg-Mather	Freeport	1,417
142	do.	—	Wind Ridge	Waynesburg "A"	191
143	do.	—	do.	Washington rider	47
				Washington	54
				Waynesburg "B"	84
				Uniontown	282
				Sewickley	409
				Fishpot	422
144	do.	—	do.	Waynesburg "B"	176
				Waynesburg	306
				Sewickley	495
				Fishpot	510
145	do.	—	do.	Ten Mile	447
				Jollytown	574
				Waynesburg "B"	752
				Upper Waynesburg	881
				Lower Waynesburg	882
				Uniontown	951
146	do.	—	do.	Waynesburg	312
				Uniontown	381
				Sewickley	509
147	do.	—	do.	Waynesburg	360
				Uniontown	425

Table 1. *(Continued)*

Test drill hole or sampling site[1]	County	Township	Quadrangle	Coal bed	Depth to base of coal bed (feet)
I48	Greene	—	Wind Ridge	Washington	184
				Waynesburg	310
I49	do.	—	—	Upper Freeport	706
I50	do.	—	—	Pittsburgh	675
I51	do.	—	—	do.	680
I52	do.	—	—	do.	762
I53	do.	—	—	do.	678
I54	do.	—	—	Waynesburg	350
				Sewickley	592
				Pittsburgh	682
I55	do.	—	—	do.	762
I56	do.	—	—	do.	961
I57	do.	—	—	Sewickley	675
I58	do.	—	—	do.	1,181
I59	do.	—	—	Washington	369
I60	do.	—	—	Waynesburg	602
J1	Indiana	Burrell	Blairsville-Bolivar	Kittanning	624
J2	do.	Green	Commodore	Lower Freeport	398
J3	do.	do.	do.	Lower Kittanning	579
J4	do.	—	—	do.	624
J5	do.	—	—	Middle Kittanning	656
				Lower Kittanning	759
K1	Lackawanna	Scranton City	Scranton	Big Bed	111
K2	do.	do.	do.	Upper New County	129
				Clark	202
				Lower New County	562
L1	Schuylkill	Reilly	Minersville	Peach Mountain	685
L2	do.	do.	do.	Seven Foot leader	817
L3	do.	do.	do.	Tunnel	608
L4	do.	—	—	Orchard	1,373
				Primrose	1,541
				Mammoth	1,719
M1	Washington	—	Claysville	Washington	285
				Upper Waynesburg	470
				Lower Waynesburg	475
				Sewickley	660
M2	do.	—	do.	Waynesburg "A"	488
				Upper Waynesburg	590
				Lower Waynesburg	594
				Sewickley	779
M3	do.	—	do.	Washington	100
				Waynesburg "B"	138
				Waynesburg "A"	164
				Upper Waynesburg	270
				Lower Waynesburg	275
				Uniontown	340
M4	do.	—	do.	do.	657
M5	do.	—	Claysville-Prosperity	Upper Waynesburg	394
				Lower Waynesburg	400
				Uniontown	512
M6	do.	East Finley	Prosperity	Pittsburgh rider	673
				Pittsburgh	677
M7	do.	Morris	do.	Washington A	146
				Washington	186
				Waynesburg "B"	218
				Uniontown	416
				Sewickley	539
M8	do.	South Franklin	do.	Pittsburgh rider	464
				Pittsburgh	471

Table 1. *(Continued)*

Test drill hole or sampling site[1]	County	Township	Quadrangle	Coal bed	Depth to base of coal bed (feet)
M9	Washington	South Franklin	Prosperity	Pittsburgh rider	791
				Pittsburgh	798
M10	do.	do.	do.	do.	665
M11	do.	do.	do.	Pittsburgh rider	726
				Pittsburgh	732
M12	do.	—	do.	Pittsburgh rider	518
				Pittsburgh	524
M13	do.	—	do.	do.	720
M14	do.	—	do.	Washington A	247
				Washington	298
				Waynesburg "B"	323
				Upper Waynesburg	437
				Lower Waynesburg	441
				Sewickley	639
M15	do.	Blaine	Washington West	Pittsburgh rider 2	329
				Pittsburgh rider 1	332
				Pittsburgh	340
M16	do.	do.	do.	Waynesburg	52
M17	do.	—	Wind Ridge	Fishpot	200
M18	do.	—	do.	Ten Mile	207
				Upper Washington	227
				Washington	469
				Upper Waynesburg	601
				Lower Waynesburg	603
				Uniontown	675
M19	do.	—	do.	Waynesburg "B"	141
				Waynesburg "A"	165
				Upper Waynesburg	278
				Uniontown	342
M20	do.	—	—	Pittsburgh	427
M21	do.	—	—	do.	427
M22	do.	—	—	do.	540
M23	do.	—	—	Washington	148
				Pittsburgh rider	540
				Pittsburgh	560
M24	do.	—	—	Sewickley	450
M25	do.	—	—	Lower Waynesburg	282
N1	Westmoreland	Derry	Blairsville	Lower Kittanning	1,060
N2	do.	Hempfield	Greensburg	Harlem	372
				Upper Bakerstown	440
				Brush Creek	627
				Mahoning	674
				Upper Freeport	728
				Upper Kittanning	806
				Middle Kittanning	866
				Clarion	966
				Brookville	994
				Mercer	1,042
N3	do.	Madison Borough	Smithton	Lower Freeport	490
				Upper Kittanning	570
				Middle Kittanning	641
				Clarion	691
N4	do.	do.	do.	Upper Kittanning	780
				Middle Kittanning	790
				Clarion	835
N5	do.	—	—	Upper Freeport	598

[1] Industry drillholes are A1 through F9; USBM drillholes are G1 through N5.

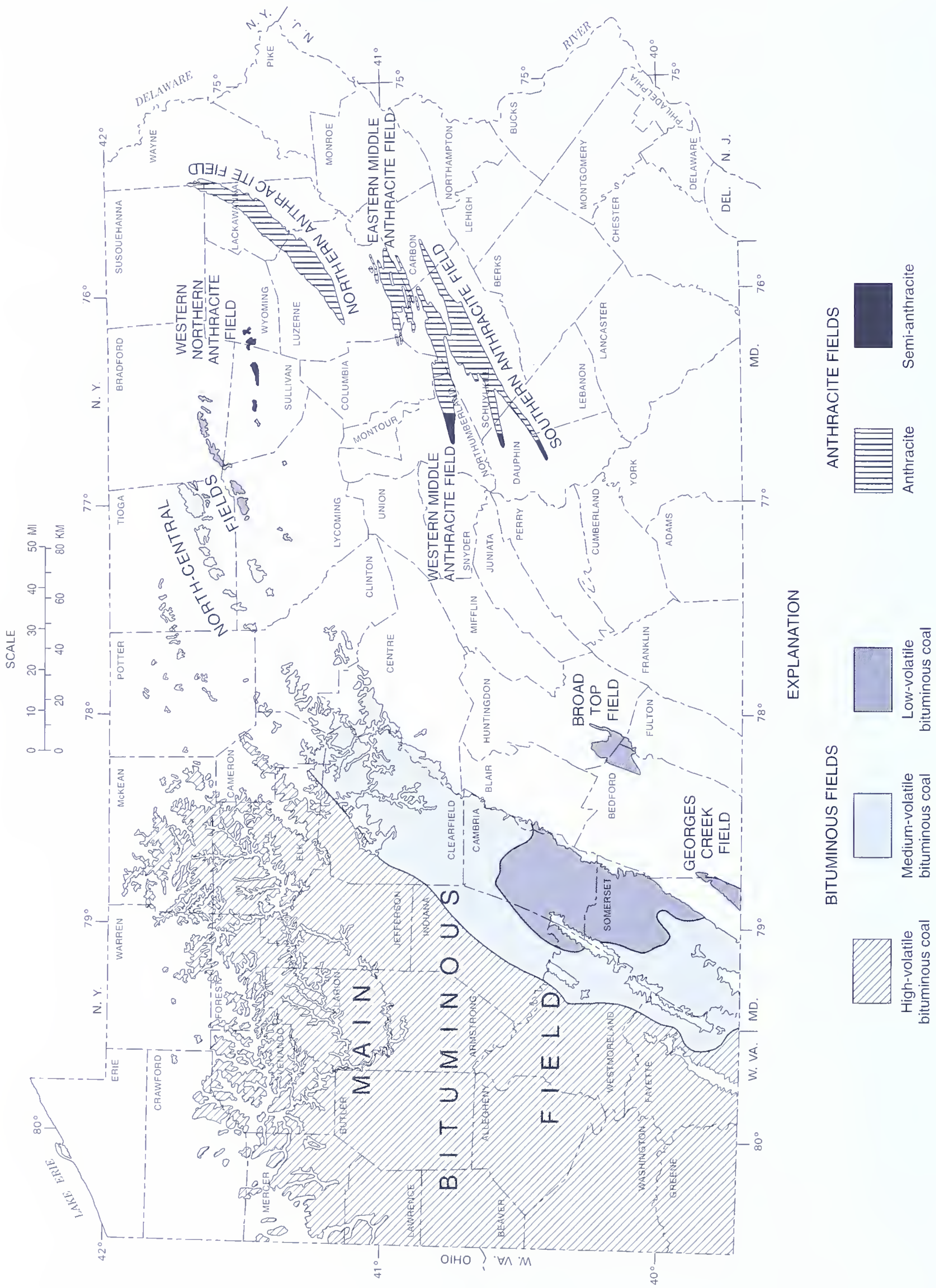

Figure 3. Distribution of Pennsylvania coal fields and associated coal ranks (modified from Pennsylvania Geological Survey, 2000).

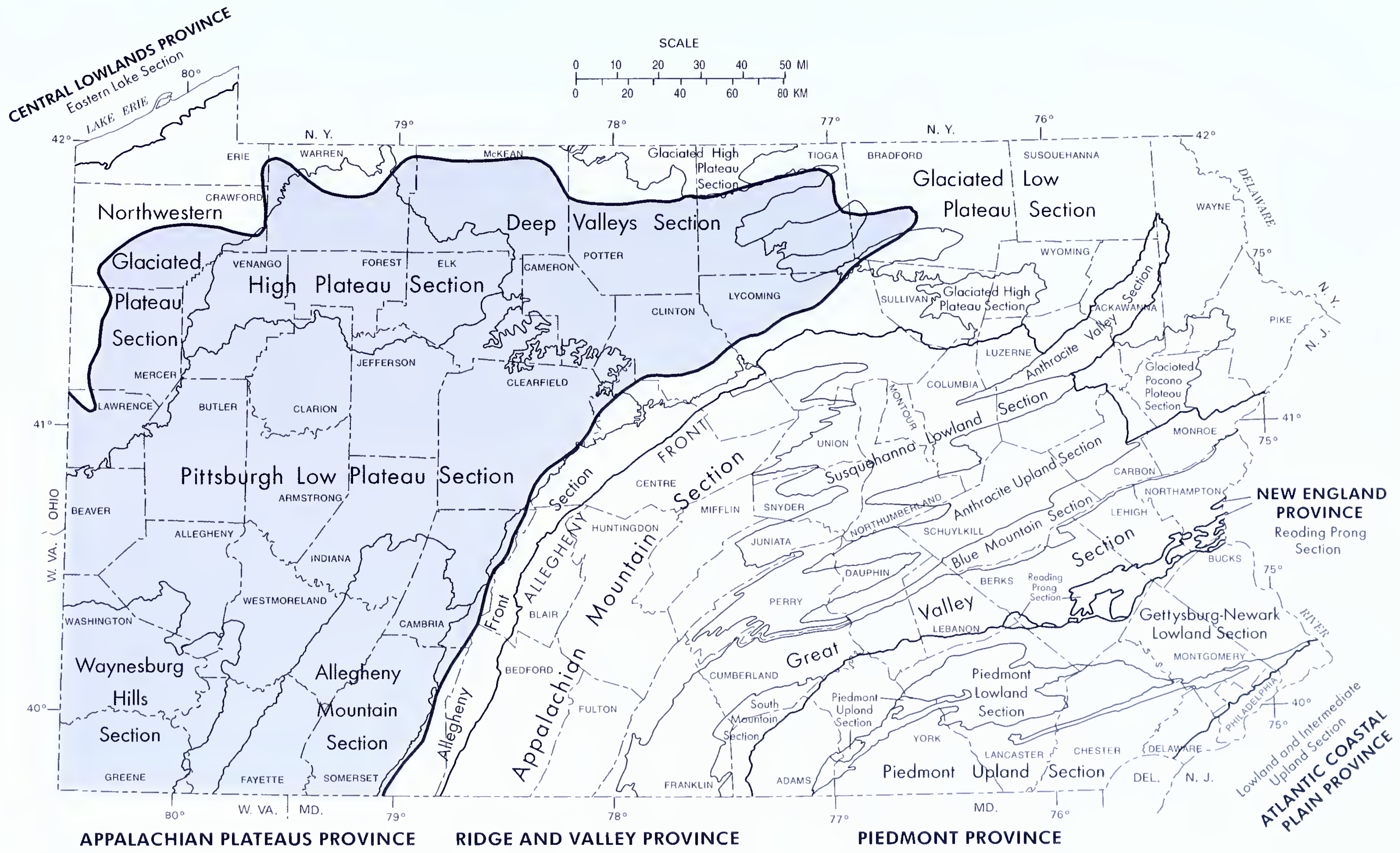

Figure 4. Map of the physiographic provinces of Pennsylvania showing the boundary of the Northern Appalachian coal basin (heavy line) (modified from Adams and others, 1982, and Sevon, 2000). The bituminous coal fields are contained within the basin and are in the Appalachian Plateaus province. The Anthracite region is located within the Ridge and Valley province and part of the Appalachian Plateaus province (compare with Figure 3).

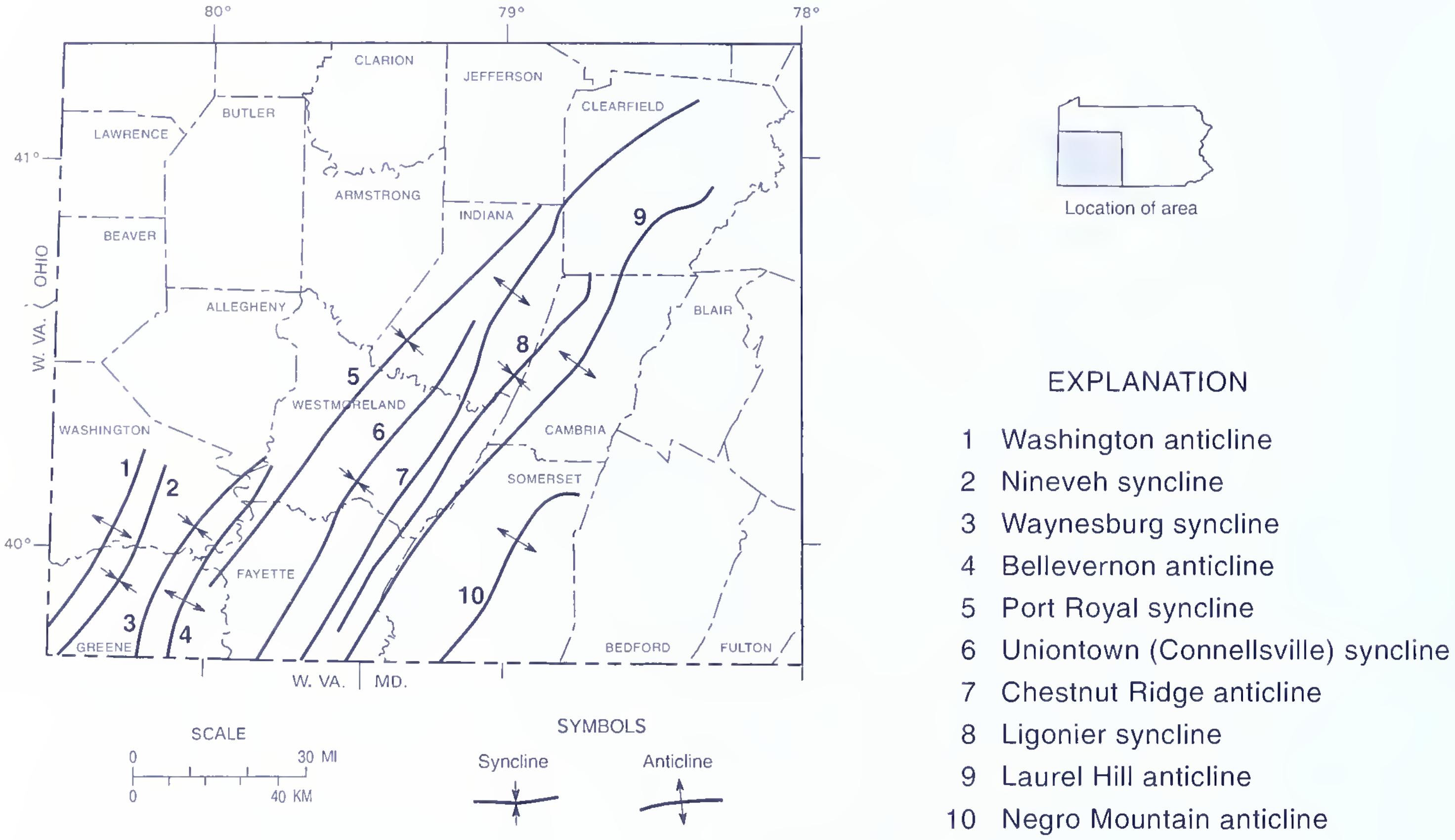

Figure 5. Some of the major fold axes in western Pennsylvania (modified from Bruner and others, 1995).

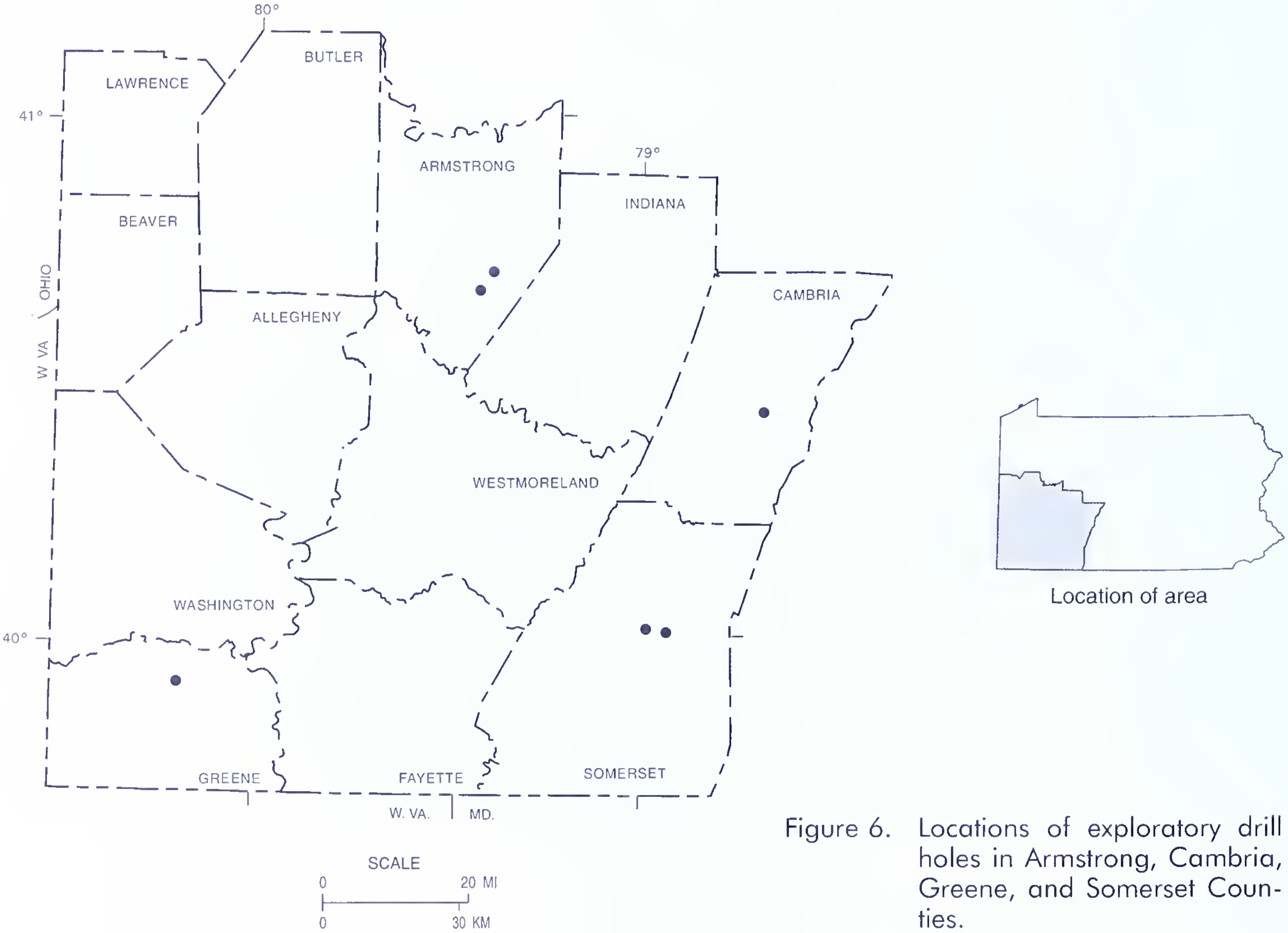

Figure 6. Locations of exploratory drill holes in Armstrong, Cambria, Greene, and Somerset Counties.

out the world's coal regions, explosions occurred with great regularity, and the reason for these disasters was widely known. In underground mines, methane is a safety hazard to miners because it can cause suffocation and is explosive in low concentrations, 5 to 15 percent in air (Bibler and others, 1997). In 1802, English inventor William Murdock revealed how coal gas (then known as firedamp) could be easily removed and burned as a light source (Petroleum Information Corporation, 1986). By the end of the nineteenth century, the new technology of CBM was in full throttle.

In the United States, CBM has been produced serendipitously since the early part of the twentieth century. Shallow artesian wells in the Powder River basin of Wyoming have yielded much gas, and water wells drilled deeper into a coal bed hit enough gas to heat a rancher's buildings (Choate and others, 1984). In 1953, Phillips Petroleum drilled and completed a methane discovery well in northeastern San Juan County, N. Mex. The Big Run field of Wetzel County, W. Va., has yielded gas from coal beds for more than 35 years.

By the third decade of the twentieth century, coal as the primary energy source was replaced by cleaner, more efficient forms of energy such as natural gas and electricity. Multidisciplinary work by the USDOE spurred interest in the direct use of CBM. Coal is attracting interest again as a double resource—the removal of one type of reserve to increase the extraction of another.

APPLICATIONS AND BENEFITS

Methane has 20 to 30 times the heat-trapping capacity of carbon dioxide (Roane, 1990)—this is true over a 100-year period in terms of the global warming impact (Bibler and others, 1997). It comprises 18 percent of the world greenhouse gases and is second to carbon dioxide in its contribution to these gases (Clark, 1989). Carter (1990) noted that worldwide venting of methane accounted for 10 to 15 percent of total methane emissions.

Degasification can have a significant, positive effect on mining activities. Immediate benefits to the mining community include decreased risk of methane explosions, increased productivity, and reduced costs. By recovering this gas, the environment can be spared another direct and linearly increasing greenhouse gas. Additionally, methane recovery from mines can stimulate local and state economies and enhance revenues.

As an energy source, CBM rivals conventional natural gas in composition and heating (calorific) value and lacks nuisance gases such as carbon monoxide, sulfur compounds, and nitrogen oxides. In some cases where methane occurs with high amounts of carbon dioxide, blending it with a gas of high heating value or using an adsorption trap will overcome this problem. Average heating values are about 1,000 Btu/cf (British thermal units per cubic foot), but range from 850 to 1,050 Btu/cf (Petroleum Information Corporation, 1986). CBM applications are the same as the conventional natural gas applications listed here: (1) direct addition to natural gas pipelines; (2) use as a boiler fuel in gas turbines to generate electricity (Kim and Deul, 1986; U.S. Environmental Protection Agency, 2000); (3) use as a chemical feedstock for methanol, ammonia, and other chemicals; (4) use as a raw material for the production of liquefied natural gas and gas products (Kim and Deul, 1986); (5) on-site applications; and (6) local use (fuel for local industries) (U.S. Environmental Protection Agency, 2000). Lower quality methane, as produced from underground mining activities, has been demonstrated in the United States and other countries to be useful in the following applications: (1) electrical power generation (on-site or sold to utilities); (2) fuel for on-site preparation plants or mine vehicles, or for nearby industrial or institutional facilities; and (3) state-of-the-art applications, such as fuel-cell technology (Bibler and others, 1997). Lower quality gas can be enriched to pipeline standards by methane separation (from carbon dioxide, oxygen, and/or nitrogen) or blending (mixing of lower and higher quality gas to yield an acceptable heating value).

SELECTED PREVIOUS STUDIES IN PENNSYLVANIA

As early as 1959 and through 1973, five wells were completed in the Pittsburgh seam by the USBM/Vesta Mines Project in Washington County. All of the wells were fracture stimulated using from 7,000 to 10,000 gallons of gelled water and 10/20-mesh sand proppants. The No. 1 NE well achieved a peak CBM production of 25 Mcfd (thousand cubic feet per day). Additional data can be found in Hunt and Steele (1991).

In the early to mid-1970s, the USDOE and USBM conducted various studies to assess the methane content of coal beds in the Northern Appalachian coal basin. The Pittsburgh seam (Figure 7) was especially attractive due to its wide areal distribution, thickness, and gassy nature. The result of a 1987 estimate was that mines in the Pittsburgh seam in the basin vented in excess of 100 Mcfd of methane. Five tests were conducted within the targeted area (stippled area in Figure 1) and one in the Anthracite region of Luzerne County (Figure 3) to determine the feasibility of developing methane from coal beds. Each test has produced pipeline-quality gas.

In 1976, the first comprehensive study of CBM was conducted by the TRW, Inc., Coalbed Methane

SYSTEM	SERIES	GROUP OR FORMATION	FORMATION OR MEMBER	MAJOR BEDS
PENN.-PERMIAN	UPPER PENNSYLVANIAN/ LOWER PERMIAN	DUNKARD GROUP (PART)	GREENE FORMATION	
			WASHINGTON FORMATION	Upper Washington limestone Washington coal bed
			WAYNESBURG FORMATION	Waynesburg "A" coal bed Waynesburg coal bed
? PENNSYLVANIAN	UPPER	MONONGAHELA GROUP	UNIONTOWN FORMATION	Uniontown coal bed
			PITTSBURGH FORMATION	Sewickley coal bed Redstone coal bed Pittsburgh coal bed
		CONEMAUGH GROUP	CASSELMAN FORMATION	Skelley marine zone
			GLENSHAW FORMATION	Ames marine zone (prominent) Pittsburgh red shale Noble marine zone (less prominent) Upper Bakerstown coal bed Carnahan Run marine zone (less prominent) Woods Run marine zone (prominent) Lower Bakerstown coal bed Nadine marine zone (less prominent) Pine Creek marine zone (prominent) Brush Creek marine zone (prominent) Brush Creek coal bed Mahoning sandstone (Big Dunkard*) Zone of brackish-water fossils Mahoning coal bed (F)
	MIDDLE	ALLEGHENY FORMATION		Upper (E) Lower (D) } Freeport coal beds Upper Kittanning (C') coal bed Johnstown limestone Middle (C) Lower (B) } Kittanning coal beds Vanport limestone Clarion (A') and Brookville (A) coal beds
	? LOWER	POTTSVILLE FORMATION		Homewood sandstone (First Salt sand*) Upper Lower } Mercer coal beds Upper Connoquenessing sandstone (Second Salt sand*) Quakertown coal bed Lower Connoquenessing sandstone (Third Salt sand*) Sharon coal bed
MISSISSIPPIAN	UPPER	MAUCH CHUNK FORMATION		Mauch Chunk red beds
			LOYALHANNA MEMBER	Loyalhanna Limestone (Big lime*)
		POCONO FORMATION		Burgoon Sandstone Shenango sandstone

Figure 7. Generalized nomenclature of major (minable) Pennsylvania coal beds and associated strata in the Main Bituminous and Georges Creek fields (refer to Figure 3 for location of coal fields). Asterisks indicate drillers' terminology.

Program (TRW Energy Development Group, 1977). The resource utility of the Pittsburgh seam, in addition to a determination of the technical and economic aspects of production, collection, conversion, and/or utilization systems, was the focus of this study (Adams and others, 1984).

During the late 1970s, the USBM conducted desorption tests for 393 coal samples from about 100 pre-mining drill holes in Pennsylvania (Diamond and Levine, 1981). General trends from most of these coals are discussed in the section "Discussion of All Test Results" on page 56. Other mine-emission data and methane-drainage projects from multipurpose vertical, horizontal, and directional boreholes in the Pittsburgh and the deeper coal beds were reported by Diamond and others (1977), Diamond and Oyler (1987), Diamond, Iannacchione, and others (1986), Diamond, LaScola, and Hyman (1986), Elder (1977), Fields and others (1975), Grau and LaScola (1984), Iannacchione and Puglio (1979), Kim (1975), Krickovic and Findlay (1971), and Steidl (1978). Desorption tests for the basin show a range of 80 to 445 cf/t and an average of about 150 cf/t for all coals (Byrer and others, 1984). Work to determine the gas content of coal beds is still being conducted at offices of the National Institute for Occupational Safety and Health (NIOSH) (part of the former USBM). Information obtained from directional drilling and the presence of coal cleats and other geologic features could be used to help determine methane emissions in a mine.

In 1977, the USBM published more work on United States methane-emission data (Irani and others, 1977). The bulk of the approximately 216 MMcfd (million cubic feet per day) of mine emissions for the total United States is from the Northern Appalachian coal basin (Adams and others, 1984). Current information on mine emissions can be found in Table 2 (p. 30–31) and in the "Mine Emissions" section (p. 62–63).

Between July 1970 and December 1979, the USBM and the USDOE had sponsored 21 artificial stimulation treatments of coal beds to enhance production of CBM in the Northern Appalachian coal basin (Adams and others, 1984). Based on the success of a Greene County pilot well after treatment, two of the above studies, also in Greene County, Franklin Township, occurred in the former Emerald mine (now RAG Emerald Resources LP) wells, including a multiple (seven) horizontal hole project from one slant hole into the Pittsburgh seam. Twelve of the 21 wells had improved gas flows ranging from 3.8 to 68 times initial production; the other nine wells did not have prestimulation production test results for comparison. According to Adams and others (1984), the highest observed post-stimulation production rate was 100 Mcfd for the No. EM-5 well in the Pittsburgh coal bed at the Emerald mine. Ten stimulated CBM wells had methane contents ranging from 92.5 to 98.2 percent, and carbon dioxide was the main contaminant in most of the wells, ranging from 0.6 to 6.45 percent in content. Although 7 of the 10 sampled wells were stimulated with nitrogen foam, the highest nitrogen concentrations do not exceed 1.2 percent of the total gas. This suggests that these CBM wells clean up suitably on flowback.

By 1977, the MRCP was under way. This project included preliminary research on CBM conducted on samples collected at field sites close to the USDOE, the former Morgantown Energy Technology Center (now National Energy Technology Laboratory) (METC), Pittsburgh Energy Technology Center (now Pittsburgh Research Laboratory), USBM, and Pittsburgh Research Center. Several individual projects listed below, which grew out of the MRCP, provided significant additional data on CBM content and the production potential of various coal beds in the Northern Appalachian coal basin.

Between 1975 and 1980, the Pennsylvania State University and the USBM tested three vertical degasification wells, two of which were stimulated, for gas at the Cumberland mine of U.S. Steel Corporation in Wayne Township, Greene County. The first well was drilled to below the Pittsburgh coal at 754 feet; the second penetrated the Waynesburg, Sewickley, Pittsburgh, and Bakerstown coal beds (Figure 7). The third (unstimulated) well was drilled as an observation well. With stimulation, production from the Pittsburgh seam increased as water flow decreased. Desorption analyses on 20 coal beds from the three wells indicated that gas-in-place ranged from 58 to 219 cf/t (Adams and others, 1982).

In 1978, Westinghouse Electric Corporation conducted a test to supply gas for space heating in a Westinghouse facility near Waltz Mill, South Huntingdon Township, Westmoreland County. Two vertical wells were drilled—the first as a production well and the second as an observation well. The first well penetrated 24 feet of coal from the Freeport seam to the Sharon seam (Figure 7). Hydraulic stimulation was used to generate new fractures in the coal to enhance the release of gas. Desorption values for the coal revealed an average methane gas content of 186 cf/t. Further core analyses suggested an in-place resource of 8 MMcf/acre (million cubic feet per acre) (Adams and others, 1984). The second well, an observation well, was cored through 27 feet of coal down to the Sharon seam and had gas contents ranging from 13 to 102 cf/t (Adams and others, 1984).

In 1979, Westinghouse Electric Corporation conducted a test project for Bethlehem mines in Ebensburg, Cambria County, that was first designed to utilize gob gas from a degasification hole to operate a turbine generator (Adams and others, 1982). A mine fire destroyed it; consequently, a vertical well was drilled that penetrated coal beds from the Upper Freeport to the Lower Kittanning (Figure 7). An alternate site was required when the well performance failed to improve. In 1980, the project was moved to Bethlehem mines, Marianna No. 58 mine, Marianna Borough, Washington County. Four horizontal boreholes produced 423 Mcfd of CBM to power the generator.

In 1979, two wells were drilled and tested by Kinloch Development Corporation in Whiteley Township, Greene County, for resource assessment. Sidewall cores of coal for desorption analysis were taken from both wells. The Kinloch No. 1 Murdock well penetrated 61 feet of coal ranging from the Waynesburg to the Upper Mercer (Figure 7). Gas yields from sidewall cores in the Waynesburg, Sewickley, and Pittsburgh coals were measured at 33 cf/t, 62 cf/t, and 62 cf/t, respectively (Adams and others, 1982). The Kinloch No. 1 Stoner well penetrated 34 feet of coal from the Pittsburgh seam to the Lower Kittanning seam (Figure 7). Gas yields ranged from 106 to 426 cf/t (Adams and others, 1982). A combined gas-in-place of 14.43 MMcf/acre or 9.24 Bcf/mi^2 (billion cubic feet per square mile) was established (Adams and others, 1982).

Between 1979 and 1981, a core hole was drilled next to the Waynesburg College campus in Waynesburg, Greene County. The purpose of this project was to determine the optimum method for extraction of methane from multiple coal seams. The core hole was located in nearly horizontal strata between the Waynesburg syncline and the Bellevernon anticline (Figure 5), and 39.9 feet of coal between the Waynesburg seam at 149 feet and the Mercer seam at 1,407 feet was encountered. After the hole was hydraulically stimulated, the gas content of the coal beds ranged from 70 cf/t for the Waynesburg to 195 cf/t for the Upper Kittanning. Having a methane content of 94 percent, the gas met quality control for pipeline injection and for fuel in heating campus buildings; consequently, a single vertical production well was drilled in 1980 (Adams and others, 1984).

Two vertical wells were drilled in cooperation with Rochester and Pittsburgh Coal Company near Homer City, Indiana County. Seams targeted in the first well were the Upper Freeport, Upper Kittanning, and Lower Kittanning (Figure 7). The main interest was to provide stratigraphic and coal-bed information. Depth, thickness, and gas content were noted. Coal beds encountered in the second well were the Upper Freeport, Upper Kittanning, and Lower Kittanning. Gas yields ranged from 50 to 445 cf/t (Adams and others, 1982). A total gas-in-place estimate for the coal seams is approximately 3.13 MMcf/acre or 2.0 Bcf/mi^2 (Adams and others, 1982).

The USBM drilled two wells in the Minersville area in Schuylkill County, eastern Pennsylvania (Figure 2 and Table 1; Figure 3), to assess the methane drainage potential of anthracite coal. Twenty coal beds were penetrated in the first well; a desorption test on the Peach Mountain coal (Figure 8) revealed a gas content of 640 cf/t. The hole was retained as an observation well. Twenty coal beds were penetrated in the second well; the gas content for the Tunnel coal (Figure 8) was 482 cf/t. The gas contents are high, but the low permeability of the coal inhibits the flow of gas with or without artificial stimulation (Trevits and others, 1986).

Other project tests and CBM case studies and results are described in Hunt and Steele (1991).

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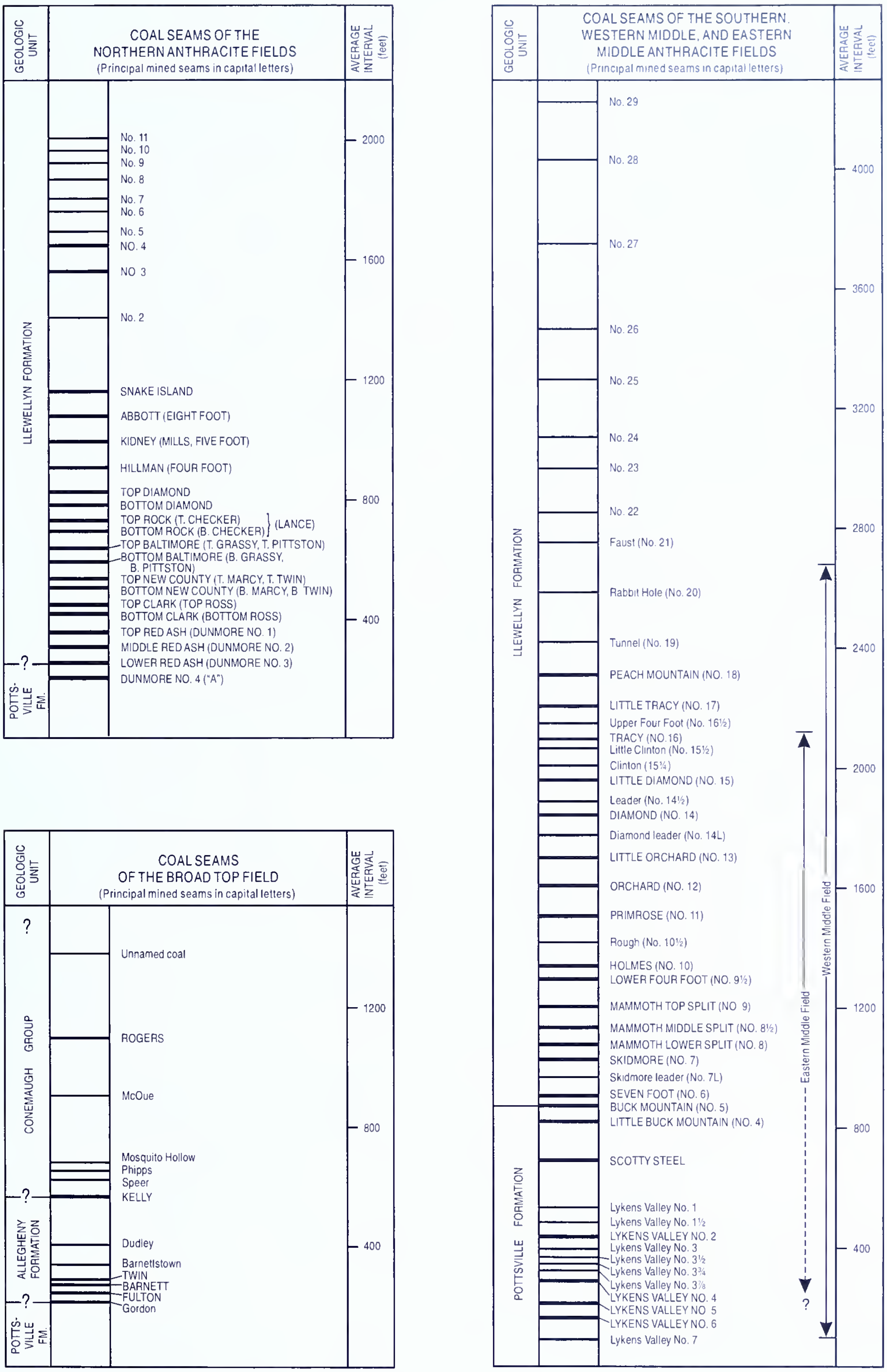

Figure 8. Coal-seam nomenclature of the Northern, Southern, Western Middle, and Eastern Middle Anthracite fields, and low-volatile bituminous coals of the Broad Top and North-Central fields (refer to Figure 3 for location of coal fields; modified from Edmunds and others, 1979).

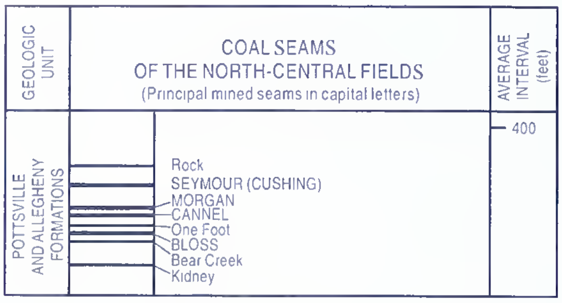
GEOLOGIC UNIT
COAL SEAMS OF THE NORTH-CENTRAL FIELDS
(Principal mined seams in capital letters)
AVERAGE INTERVAL (feet)
400
POTTSVILLE AND ALLEGHENY FORMATIONS
Rock
SEYMOUR (CUSHING)
MORGAN
CANNEL
One Foot
BLOSS
Bear Creek
Kidney

Figure 8. *(Continued).*

physical scientist, U.S. Department of Energy, National Energy Technology Laboratory). Jay L. Snyder, Chief of Toxic Materials Branch, and Jim Lohrett, physical science technician, of the U.S. Department of Labor, Mine Safety and Health Administration, Physical and Toxic Agents Division, Pittsburgh, Pa., performed the gas chromatography analyses; and Forrest E. Walker, former Director of Technical Services, Geochemical Testing, Somerset, Pa., provided the coal analyses. The following Pennsylvania Geological Survey technical and managerial staff members are especially thanked: Leslie T. Chubb, laboratory technician, for graciously assisting with equipment assembly during the early stages of this project; Christopher D. Laughrey, John A. Harper, Samuel W. Berkheiser, and former staff geologist Patricia F. Buis for constructive comments and suggestions during project work and in formal review to improve this report; Viktoras W. Skema, for contributing valuable suggestions to improve the quality of the "Geologic Framework" section for western Pennsylvania; Jon D. Inners and Donald M. Hoskins, for offering helpful comments during the final stages of writing; Anne B. Lutz, for streamlining the report through careful editing; and James H. Dolimpio, cartographic drafter, for computer drafting of figures. Finally, the author thanks the U.S. Geological Survey for its financial contribution for the printing of the report.

COAL-BED METHANE

CHEMISTRY

Methane, the primary component of natural gas and CBM, is the simplest and most stable hydrocarbon. It is flammable, nonpoisonous, colorless, and odorless. The gas is explosive at mixtures of about 5 to 15 percent in air (Bibler and others, 1997); it is not toxic when inhaled, but it can cause suffocation because its presence reduces the amount of oxygen inhaled. Methane is the first of the saturated, straight-chained homologous series of compounds called alkanes. It consists of one carbon atom and four hydrogen atoms. The reported stable isotope compositions of CBM are highly variable; methane from North Germany coals are isotopically heavy (enriched in ^{13}C), whereas North American CBM is isotopically light (enriched in ^{12}C) (Hunt, 1979; Schoell, 1980, 1984, 1988). The CBM of Pennsylvania falls into the latter category, having ^{13}C values of -39.9 to -55.1 percent (Christopher D. Laughrey and Frederick J. Baldassare, personal communication, 1991).

Other hydrocarbons, carbon dioxide (CO_2), nitrogen (N_2), oxygen (O_2), hydrogen (H_2), and helium (He) are also found in coal-bed gas, but since the primary constituent is methane, the gas is more commonly referred to as "coal-bed methane" (Appendix 2). Trace amounts of isotopically heavy (in carbon) alkanes, such as ethane, propane, butane, and pentane, and the unsaturated hydrocarbons, such as ethylene, propylene, and 1-butene, were also detected (Appendix 2).

ORIGIN AND GENERATION

The formation of CBM occurs naturally as a part of the earth's carbon cycle. Biogenetic (biogenic) methane is generated by the microbial decomposition of plant material, mainly cellulose and lignin, in the biosphere. Fermentation and the reduction of carbon dioxide are the principal reactions yielding methane at this stage. Methane is also generated in the lithosphere during the coalification of plant material. This diagenetic stage of coalification yields methane and other gases as a by-product of the complex chemical reactions responsible for producing lignite, subbituminous, bituminous, and anthracite coals. According to Kim (1973) and Stach and others (1982), the biogenetic stage of coalification occurs after bacterial degradation of the base organic material to peat. The biogenetic stage includes microbial decomposition of plant material (cellulose and lignin) to CO_2, alcohol, acids, and methane under low temperatures and shallow burial conditions (Petroleum Information Corporation, 1986). Vegetal decomposition includes fermentation and reduction of CO_2 to produce biogenetic methane (Kim and Kissell, 1986). Atmospheric N_2, O_2, and CO_2 may be adsorbed on the peat during deposition. N_2 and O_2 may not be present during deposition, but they may be introduced by percolating groundwater (Kim and Kissell, 1986). CO_2 is produced by oxidation of organic material and replaces most of the O_2; high amounts of CO_2 are sometimes associated with coals affected by tectonic activity (Kim and Kissell, 1986). H_2 is a remnant of the coalification process, and traces of He are linked to decay of radioactive minerals in coal (Kim and Douglas, 1973). With the depletion of O_2, the amount of methane decreases until the temperature reaches 50°C (122°F) and thermogenetic processes begin (Petroleum Information Corporation, 1986). This temperature corresponds to the lignite-subbituminous boundary (Figure 9) and represents diagenetic to catagenetic changes. Diagenetic changes include the biological, chemical, and physical changes undergone by a sediment after its initial deposition. Catagenetic changes occur after a sedimentary rock is buried and are characterized by pressure-temperature conditions that are much different from those at deposition.

The geochemical (catagenetic) stage includes a complex series of chemical reactions catalyzed by increased temperature (due to thicker overburden or higher geothermal gradients) and pressure. Conditions are ripe for compaction and conversion of peat to coal, methane, volatile matter, and other gaseous byproducts. Most of the methane is formed at about 120°C (248°F), the approximate boundary between high- and medium-volatile bituminous coal (Rightmire, 1984). The peak temperature for methane formation occurs at about 150°C (301°F), which corresponds to the medium-volatile/low-volatile bituminous boundary (Figure 9). At this stage, most of the methane is adsorbed on the internal surface of micropores within

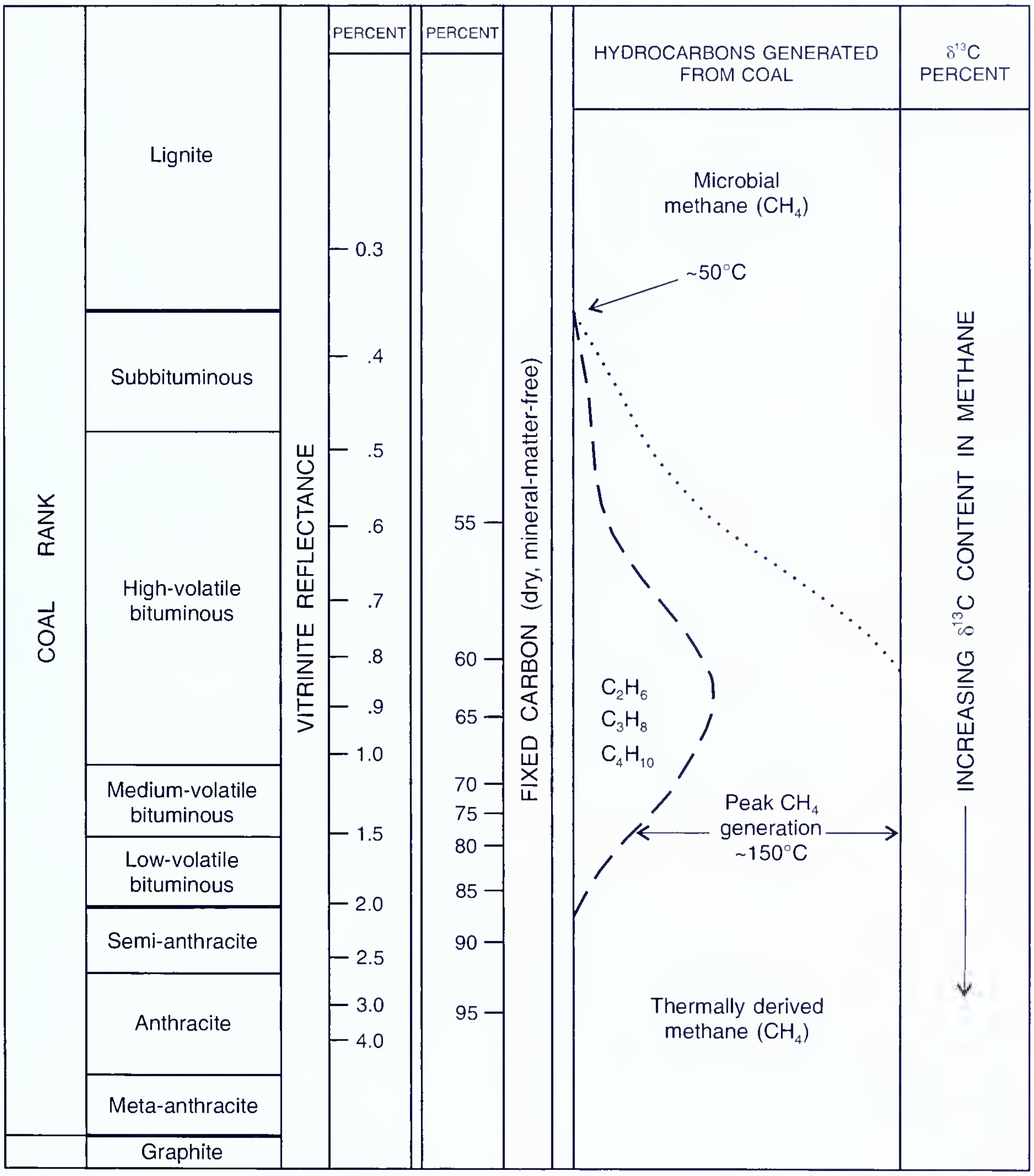

Figure 9. Diagenetic and catagenetic changes during coalification with temperature, coal rank, and oil and gas generation. The degree of organic maturity is measured by percent vitrinite reflectance and fixed carbon in coal and the carbon isotope ratio ($\delta^{13}C$) of methane in parts per thousand (modified from Diamond, Iannacchione, and others, 1986).

the coal, and water fills the natural fractures or cleats. Temperatures beyond this methane window cause an increase in volatile-matter production. With the advent of higher temperatures and anthracite formation, most of the volatiles and the moisture, oxygen, and hydrogen contents are depleted or entirely lost. As the fixed carbon content, Btu value, and aromatic character of the coal increase with increasing coalification, the ratio of methane to carbon dioxide also increases (Kim, 1973). In addition, as coal rank and vitrinite reflectance increase, the methane becomes isotopically heavier (Diamond, Iannacchione, and others, 1986). According to Kim and Kissell (1986), methane may form in the geochemical stage by several possible reactions: (1) demethanation—the splitting off of methyl side chains followed by their saturation; (2) fragmentation of straight or normal carbon chains; (3) condensation of straight chains to ring compounds in the coal, during which methane and water are liberated (Tissot and Welte, 1984); (4) reduction of unsaturates or hydrogen-poor hydrocarbons; (5) reduction of carbon dioxide; or (6) secondary decomposition of higher alkanes (the main component of petroleum and natural gas) to lower molecular-weight gases.

Earlier temperatures and pressures, intensity of fracturing, and permeability of the coal and overlying strata contribute to the overall gas content of a coal bed; thus the amount of CBM is affected by its diagenetic history (Kim and Douglas, 1973). Soot (1989), however, suggested that these data only apply to short-term, initial production. This implies that other geologic factors may be more important in designing a degasification program for long-term production.

Because a coal bed is considered to be the source as well as the reservoir rock for methane, it is appropriate to describe the gas as "coal-bed methane." The gas is sometimes referred to as "coal gas" or "coal-bed gas" because it contains components other than methane. The term "coal-bed methane," or "CBM," will be used in this report.

FLOW DYNAMICS

CBM reservoirs differ from the more conventional gas reservoirs by the amount of gas and the manner in which it is stored (Rice and others, 1993). Coal is a heterogeneous, combustible solid having a dual porosity system in which methane can occur. The primary (matrix) porosity, or microporosity system, is the internal diffusion network of the coal, in which the average pore (micropore) diameter ranges from 5 to 20Å (Kim, 1973; Murray, 1991). Up to 98 percent of the gas is contained on the surface of the micropores (Gray, 1987). The gas is absorbed (or sorbed) within or upon the molecular structure of the kerogen (insoluble organic material) in the coal and in the micropores. When a coal bed is dewatered during CBM operations, methane desorbs from the matrix and diffuses into the cleat system (small vertical joint sets; see below). Mesopores (associated with pore volume) range from 20 to 500Å (Bell and others, 1985; Davis and others, 1986; Gan and others, 1972; Harris and Yost, 1976; Jones and others, 1988). Macropores are larger than 500Å (Murray, 1991). The pore size depends on maceral content in high-volatile bituminous coal; for example, vitrinite porosity ranges from 20 to 200Å, and inertinite porosity ranges from 50 to 500Å (Harris, 1979; Harris and Yost, 1976). The secondary (fracture or cleat) porosity, referred to by Murray (1991) as the macroporosity system, is a combination of natural microfractures, cleats, and irregularly distributed cavities (Petroleum Information Corporation, 1986). The cleat network provides permeability for fluid flow within the coal, accomodating a two-phase flow of water and gas in the fracture system during CBM production (Gash and others, 1993).

Cleats are small vertical joint sets in coal that are 30 to 90 degrees apart from each other (Diamond, Elder, and Jeran, 1986; McCulloch and others, 1976) (Figure 10). They form as a result of compaction and dehydration during the coalification process and in response to local tectonic forces. The dominant fracture plane, face cleat, generally is oriented normal to structural grain; the minor fracture plane, butt cleat, commonly is oriented perpendicular to the face cleat (Kelso and Kelafant, 1989). Face cleat permeability usually is several times greater than butt cleat permeability (McCulloch and others, 1974). That is, holes drilled perpendicular to (intersecting) the largest number of face cleats yield the highest permeabilities, gas flows, and pressures. Holes drilled parallel to the face cleat show the lowest permeabilities, gas flows, and pressures.

CBM can be retained in coal in the following ways: (1) as adsorbed or absorbed molecules on the internal surfaces or within the molecular structure of the coal; (2) as gas trapped within the matrix microporosity or macroporosity; (3) as free gas within the natural fracture system; and (4) as dissolved gas in the free water in cleats and fractures or formation water (Figure 10) (Choate and others, 1986; Murray, 1991). "Internal surface area of coal can be as high as 1.5 million square feet per pound of coal and 0.34 standard cubic feet of gas per pound of coal can be adsorbed on the internal surface area at the saturation pressure of 1500 psig [pounds per square inch gage]" (Cervik, 1969, p. 8). Murray (1991) attributed the ability of a CBM reservoir to store more gas than a conventional reservoir to the unique molecular structure of coal. "The micropore system appears to behave as a molecular

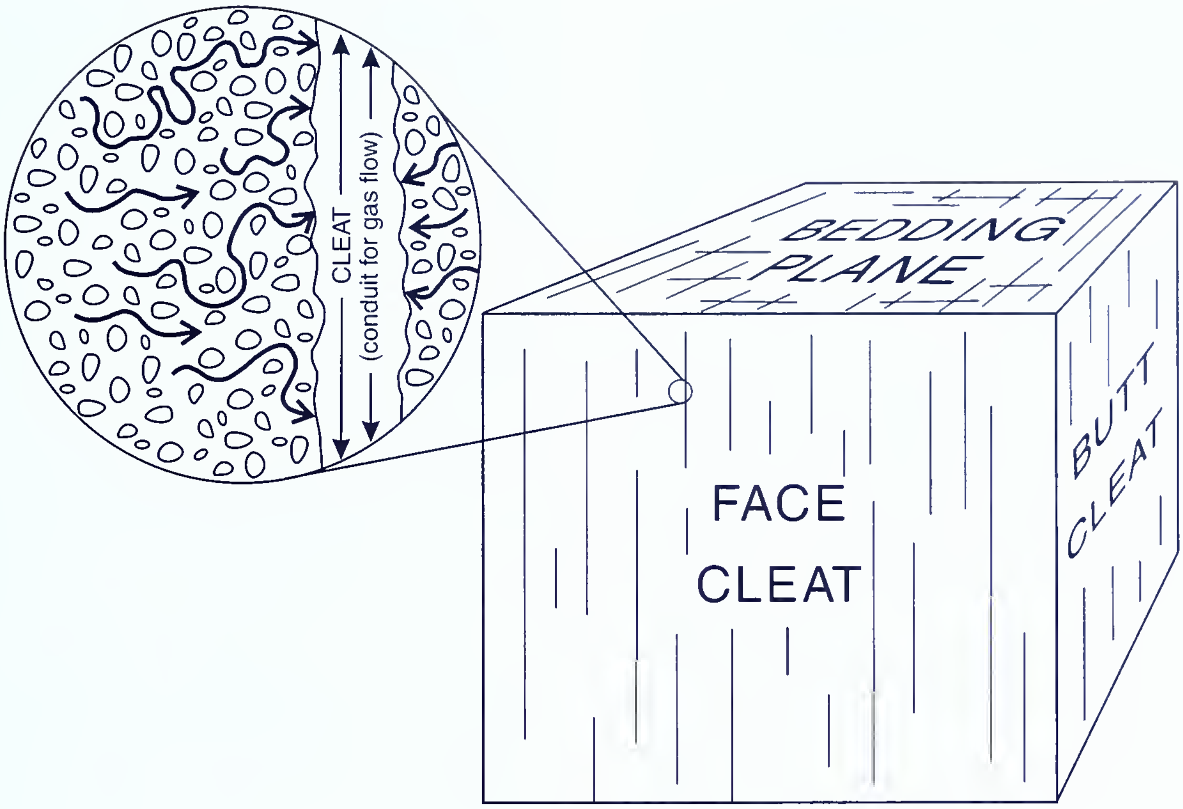

Figure 10. Cleat system and two-phase flow model of gas in a three-dimensional block diagram of coal. Arrows indicate molecular diffusion through the coal matrix to fractures and cleat surfaces. Gas desorbs from cleat surfaces, and eventually, fluid moves from the natural fracture system to the well bore during coal-bed methane production.

sieve, or a clathrate cage (analogous to the structure of zeolite minerals), in which methane molecules are nested within benzene rings" (Murray, 1991, p. 99). According to Kim and Douglas (1973, p. 2), "the diffusion coefficient, activation energy of desorption, adsorbate density, permeability, surface area, and pressure control the rate at which gas can flow from the micropores."

Pressure, fracture porosity, and permeability of adjacent strata govern the general flow pattern in cracks and fractures. According to Koenig and Bell (1985), flow of gas in a coal bed follows in three main stages: (1) single-phase flow, where only water is produced due to high water saturations (true of most United States coals); (2) unsaturated single-phase flow, where gas and water are present, but only the water is mobile; dewatering must take place before desorption can occur to lower the reservoir pressure and increase permeability to the gas; and (3) two-phase flow, where gas and water are both mobile with increasing gas saturation. Once the two-phase flow occurs, two mechanisms dominate gas migration: (1) governed by Fick's Law, gas molecules are slowly diffused through the micropores of unfractured solid coal to the fractures surrounding the coal face and butt cleats in response to a concentration gradient; and (2) governed by Darcy's Law (which assumes that flow is laminar, and inertia can be ignored), mass transport through the fracture system is by laminar flow of methane and water in response to a pressure gradient (Ertekin, 1984; ICF Resources, Inc., 1988) (Figure 10).

RESERVOIR CHARACTERISTICS AFFECTING COAL-BED METHANE RECOVERY

Coal Rank and Quality

Most of the coals from the Main Bituminous field in western Pennsylvania are high-volatile A bituminous in rank. Correlations presented in Appendices 3 and 4, and throughout the literature, show that, in general, the gas content of Pennsylvania's bituminous coal is directly related to rank and depth. For example, the higher the rank, the greater the adsorptive capacity of the coal (Appendix 3, Cambria County). However, within different ranks of coal, there will be variations in gas capacity based on variations in the coal chemistry, that is, moisture, fixed carbon, and volatile matter (Appendix 1). Gas content also varies inversely with the grade of coal or the inorganic (ash) content (Appendix 1). According to Rice and others (1993), gas contents range from 2.5 cc/g (cubic centimeters per gram) (80 cf/t) in low-rank coals to 31 cc/g (993 cf/t) in higher rank coals. It is recommended that gas content of coal be reported on an ash-free basis. This normalization is important in resource calculations to avoid overestimation of resources, especially in basins where coal analysis data are sparse (Ayers and Kelso, 1989; Scott and others, 1995).

Although the coal type (maceral and lithotype composition) was not determined for the samples in this study, type affects porosity and permeability. Adsorbed methane is highest in the cleat-rich liptinites and vitrinites, and free methane is highest in the inertinites (Pashin and others, 1990).

Net Coal Thickness

The thickness of coal penetrated is also important for economic production of CBM. Numerous relatively thick coal beds are favorable; however, this is not always the case, and one or two thin coals may well prove to be profitable. In the Northern Appalachian coal basin, a thickness of 1 foot is small, but acceptable, if the bed is part of a multiseam project (the combined production from multiple coal beds of a given total thickness in a well is comparable to the production from a single seam of equal thickness). The probability of success in gas production increases with thick beds (greater than 2 feet in the Northern Appalachian coal basin) and/or high-rank coal.

Gas Content

The gas content of a coal bed is a fundamental parameter affecting productivity. The maximum gas content measured by the USBM in the Northern Appalachian coal basin is 440 scf/t (standard cubic feet per ton), and the average is 200 scf/t (Hunt and Steele, 1991). These figures tend to be lower than those of the Central Appalachian coal basin. However, lower gas contents in certain parts of the Northern Appalachian coal basin may simply be due to shallow depth. Most coals are undersaturated and underpressured here, but with proper artificial stimulation, economic yields are possible. An example of this is in the Campbells Mill pool in Indiana County (refer to "Coal-Bed Methane Pools and Production" on p. 40). According to Hunt and Steele (1991), gas contents should be from 125 to 150 scf/t in multiple coals for economic viability. For example, the blocky, high-volatile Pittsburgh coal bed averages approximately 150 cf/t of gas at 500 feet deep or more (Briggs and Tatlock, 1999). On a production level, according to some industry standards, a minimum range of 50 to 100 Mcfd of gas can be considered to have commercial potential.

Gas Reservoir Pressure

Coal has substantial gas storage capacity because of its large internal surface area (the micropore system) of approximately 1 million ft^2/lb_m (square feet per pound of matrix) (McElhiney and others, 1989). Murray (1991) pointed out that lower rank coals below medium-volatile bituminous are characterized by having a storage capacity that is greater than the amount of gas generated. For example, "0.03 cubic meter (m^3) (1 cubic foot) of sandstone having 15% porosity and 75% gas saturation, at a depth of 760 m (2500 ft), can hold 8.4 scf of gas, whereas the same volume of medium-volatile bituminous coal at the same depth can store 22 scf of gas or 2.6 times as much" (Murray, 1991, p. 99). According to Rice (1997), six to seven times more gas can be stored in coal than in a comparable volume of a conventional gas reservoir. This is due to the unique molecular structure of coal, where the micropore system behaves as a sieve or clathrate cage and methane molecules are nested within benzene rings (Murray, 1991).

CBM reservoir pressure is controlled by hydrostatic head. In the first stage of CBM production, coal beds (especially highly permeable coals) must be dewatered before any significant gas flow by desorption can occur, because the methane is adsorbed on the surface of the coal and bound by reservoir pressure (McKee and others, 1984). By dewatering the coal bed via vertical boreholes, reservoir pressure is reduced, and water saturation is lowered (Trevits and Finfinger, 1985). This raises the permeability and degree of gas saturation of the coal bed, enabling gas to flow freely to the well bore, where the pressure has been lowered to less than hydrostatic (Kissell and Edwards, 1975; Murray, 1991). The second stage of CBM production, the stable production stage, is referred to as "negative decline," which distinguishes it from other conventional gas reservoirs. During production, desorption disrupts the chemical and physical equilibrium of the coal, enabling new methane formation, thus producing a negative decline production curve (Harrison and Gordon, 1984). In the final stage of production, the decline stage, the amount of gas declines and water production remains low. Reservoir pressures of from 125 to 175 psia (pounds per square inch absolute) are recommended for economic production (Hunt and Steele, 1991). The Pittsburgh coal has a reservoir pressure on the order of 260 psig (Cervik, 1969). In general, coal beds in Pennsylvania have low reservoir pressure.

Adsorption/Desorption Isotherm

Unique to each coal is the isotherm that indicates the ability of the coal to adsorb/desorb gas on the walls of its internal micropore surface, or gas storage capacity. Coal's ability to adsorb methane, for example, can be enhanced by increasing pressure to simulate in situ reservoir stress. Adsorption (sometimes called sorption) isotherms represent different rates of methane adsorption as a function of pressure at a constant temperature; coal adsorption varies directly with pressure and inversely with temperature and moisture content (Kim, 1977; Kim and Kissell, 1986). The role of coal rank and type (maceral composition) in controlling gas adsorption is not clear, but they do influence pore-structure development (Crosdale and others, 1998).

Because most of the gas in coal is adsorbed on the internal surfaces of the micropores, it is possible to measure the adsorption capacity of the coal as a function of pressure and simulated constant reservoir temperature (Close and Erwin, 1989). It is important to "establish whether the gas content in the coal is 'on the isotherm' and readily releasable or whether the coal is undersaturated and requires depressuring before methane is released" (Kuuskraa and Brandenburg, 1989, p. 52). This work showed that where the ratio between reservoir pressure and desorption pressure (pressure where gas desorption begins) approaches unity, optimum conditions for gas production exist (Petroleum Information Corporation, 1986). Therefore, gas content and reservoir pressure data can be integrated with adsorption isotherms to help formulate production regimes. Adsorption isotherm testing and research are ongoing and important tools to enhance successful gas recovery from coal beds and to troubleshoot gas-related problems in deep mining (Crosdale and others, 1998; refer to "Coal-Bed Methane Potential" on p. 39).

Fracture Permeability

The presence of high fracture density or a well-developed cleat system in the coal bed is important for establishing permeability, hydrostatic conditions, and length of drainage radius for a CBM well. Not only are high methane contents necessary, but a high frequency of permeability pathways is critical for commercial gas production. A reservoir must have a permeability of at least 0.1 to 0.5 md (millidarcy). Most coals commonly have less than 1 md of permeability (Petroleum Information Corporation, 1986). Coal permeability is determined from the following procedures: (1) core tests, (2) pressure-transient well tests, or (3) production-history matching using reservoir simulation (Petroleum Information Corporation, 1986).

Coal beds of Pennsylvania have lower permeabilities compared to western basins. Kaiser (1993) found that CBM production is possible in western basins over a wide pressure range, but is highest from artesian, overpressured coal beds. Ironically, some coal permeabilities may be too high for production and the coals difficult to dewater because of proximity to recharge areas. The less permeable, underpressured coal beds in Pennsylvania may yield less CBM but may also produce little or no water, thus avoiding the cost of water disposal.

It is commonly necessary to complete wells in areas where coals have natural fractures other than cleats. These may be faults, fold-induced fractures, or stress fractures due to the differential compaction properties of coal beds and adjacent shales. According to Ayers and Kelso (1989), subsurface fractures have been predicted by mapping lineaments on aerial photographs and comparing their trends with fractures in outcrops and cores. Favorable geologic structure and permeability occur on the flanks of anticlines or synclines, where the orientation and degree of jointing is more evident than on the structural axes.

The rate of cumulative desorbed gas over time depends on the degree of fracture networking. That is, if the coal is blocky and dense and has a poorly developed fracture network, there will be a slow rate of increase. If the coal is friable and has a well-developed fracture network, there will be an immediate increase in the rate of cumulative gas released.

Diffusion Characteristics

The dual porosity of coal contributes to and influences whether a coal is a source and a reservoir for CBM. Porosity is also an indicator of the degree of storage capacity. After desorption, methane diffuses through matrix blocks by means of a concentration gradient governed by Fick's Law of diffusion (Cervik, 1969). Flow through the fracture system is laminar, as described by Darcy's Law (Cervik, 1969). Friable coals that have a more pronounced fracture network emit more gas during desorption than blocky, dense coals (McCulloch, Levine, and others, 1975). In this study, no apparent correlation exists between gas content and thickness, temperature, or barometric pressure. McCulloch, Levine, and others (1975) stated that the storage temperature of the sample can affect the emission rate and should be kept constant (at approximately 70°F) throughout the desorption process.

Depth

To a certain extent, the greater the depth of overburden, the higher the methane content. This is supported by the fact that deeper mines have higher emission rates and that rank increases with increasing depth. "Where coals subcrop greater than 500 feet below the water table, the amount of gas trapped is a function of depth (hydrostatic pressure), the hydrogeologic regime, and the coal rank" (Close and Erwin, 1989, p. 39).

Nationally, most economic CBM is less than 6,000 feet deep (Petroleum Information Corporation, 1986); the range of gas-in-place is from 400 to 800 Tcf (trillion cubic feet) or more (Murray, 1991). In Pennsylvania, the window of economic opportunity includes coals that are less than 2,000 feet below drainage (Kelafant and others, 1988). At greater depths, the increase in gas content is small due to low permeabilities associated with deeper coal beds (coal has flat cracks that compress with depth of burial) (Berger Associates, 1978). Likewise, Close and Erwin (1989) noted that coals less than 500 feet below the water table typically have lower gas contents, because decreased micropore capillary pressure has enabled partial desorption and atmospheric degasification.

Distance to Outcrop

For the purposes of production and development, it is generally advised that a drilling project be located optimally in a virgin coal field or at least 2,000 to 3,000 feet from active mine workings (William P. Diamond, personal communication, 1992). This is to avoid the possibility of atmospheric degasification.

Stratigraphic Associations and Traps

Coals are able to generate and release sufficient gas to form commercial gas accumulations. However, when the amount of gas generated exceeds the storage capacity of the coal reservoir, migration can occur. For example, "under conditions of thermal heating, coals may continue to generate methane, expelling it into the surrounding sediments when the total storage capacity of the coal has been exceeded" (Murray, 1991, p. 99). This migration of gas can occur especially if the adjacent caprock is a permeable sandstone or a similarly permeable reservoir rock. Historically in Pennsylvania, there has been a close association between CBM and natural gas from sandstone and shale reservoirs. It is possible that generation, migration, and retention of gas among closely associated source rocks create ambiguities in source-rock identification—important in cases of ownership issues (refer to the "The Coal-Bed Methane Ownership Quandary" on p. 64).

In Situ Stress

"The ability of methane gas to diffuse from the matrix of a coal seam and move to a production well via the natural fracture (cleat) system is strongly influenced by changes in stress on the coal seam" (Soeder, 1991). Reducing the partial pressure of the CBM by dewatering allows release of the gas, thus creating the physical state of reservoir equilibrium. Dewatering the coal via vertical boreholes reduces reservoir pressure and lowers water saturation (Trevits and Finfinger, 1985). This in turn raises the permeability of the coal bed and allows for easier gas flow to the well bore (Kissell and Edwards, 1975). However, McKee and others (1984) proposed that through the process of dewatering, not only is methane able to flow freely to the well bore due to lowered formation pressures, but there is a lowering of permeability, porosity, and compressibility in deep, fractured coals. Decker and Horner (1987, p. 55) suggested that "to overcome the inherent low coal permeability at depth, permeability can be enhanced through structural deformation." Numerical simulations by Schwerer and Pavone (1984) have shown that the permeability of coal varies for ranges of pressure during stimulation practices. Methods of prediction using Darcy's law at a given permeability can help specify coal reservoir conditions and determine long-term production of water and gas (Decker and Horner, 1987).

Studies have shown that artificial injection fracturing applied to coal is more likely to be contained when the contact lithologies are shale rather than sandstone (Petroleum Information Corporation, 1986). This is due to the fact that "minimum horizontal stresses in coal can be expected to be lower than in adjacent shales but higher than in sands" (Petroleum Information Corporation, 1986, p. 24).

Anomalously high treatment pressures are needed for coal-bed stimulation (Petroleum Information Corporation, 1986). However, this procedure is not without debate. Medlin and Fitch (1983) contended that extremely high treatment pressures can cause severe fracture branching and an increase in post-stimulation well clean-out time because of the release of coal debris. Coal generally responds well to artificial stimulation, but sloughing of large pieces of coal and migration of coal fines are common problems. Sizable coal particles can plug downhole production equipment, and the presence of coal fines may account for why extremely high treatment pressures are required to stimulate coal-bed reservoirs (Petroleum Information Corporation, 1986). Routine hydraulic stimulation to advance gas flow to the well bore introduces stress on the coal. Soeder (1991) observed that although the larger cleats remain open, the smaller cleats begin to close, creating a more complex pathway and therefore reducing permeability.

New knowledge of the effect of stress and mechanical properties on coal, as described above, has led to improved hydraulic design for more efficient and economical recovery of CBM. For example, horizontal boreholes combine drilling and stimulation because of deep penetration of the target coal bed. Boreholes drilled perpendicular to face cleat have the highest degassing potential. High methane contents and a high frequency of permeability pathways are necessary for commercial gas production. From this, it is important for producers to learn more about how coal reservoir characteristics influence coal as a source rock.

GEOLOGIC FACTORS AFFECTING COAL-BED METHANE OCCURRENCE

Tectonic History and Structural Controls

Tectonic episodes during the Precambrian and Paleozoic set the stage for the sedimentary record in the Northern Appalachian coal basin, including the timing, distribution, thickness, and rate of progradation and regression of detrital clastic wedges. Some of these structures existed prior to the beginning of the Pennsylvanian Period and had a control on the deposition of strata during Pennsylvanian and Permian time. Other early-formed structures within the Appalachian belt were reactivated to directly affect later structures.

Paleozoic rocks in and around the study area were deformed into long, gentle, open folds. These folds formed during the main phase of the Alleghanian orogeny. This orogeny occurred after the Pennsylvanian and before the Late Triassic-Early Jurassic rifting in eastern North America. Fractures and faults, the presence or absence of which are so important in the transmission and storage of fluids in coal beds, formed before, during, and after the main phase of Alleghanian folding.

The Northern Appalachian coal basin, or Allegheny synclinorium (Kay, 1942), was a shelflike, gently subsiding structural basin or synclinorium during the Pennsylvanian and Permian that evolved into the nearly symmetrical, oval basin of today. It is a northeast-southwest-trending basin in the north-central Appalachian Plateaus physiographic province, covering approximately 43,700 square miles (Mroz and others, 1983) (Figures 1 and 4). The deepest part of the basin also includes the Dunkard structural basin (Pittsburgh-Huntington synclinorium), which is located in the southwestern part of the state and measures 35 miles wide by 250 miles long (Bruner and others, 1995). The deepest coals in the basin are buried up to 2,000 feet in Greene County (Kelafant and others, 1988). These coal beds experienced intense pressures and temperatures, which contributed to their high rank. The axis of the Pittsburgh-Huntington synclinorium lies within the Rome trough, an Early(?) and Middle Cambrian aulacogen (Shumaker, 1996; Shumaker and Wilson, 1996; Thomas, 1991), and crosses the western part of the study area (Figure 11). The relatively high rank, high volatility (Figure 3), total effective coal thickness, and deep burial of the coal in the Dunkard basin suggest that this area has great potential for trapping large volumes of CBM.

The basin configuration is structurally controlled on the east by late Middle Pennsylvanian-age coal cropping out on the flanks of northeast-southwest-trending folds. Tight to moderate folding interrupts the otherwise relatively undeformed Northern Appalachian coal basin. These features trend northeast to southwest and have dips generally between 10 and 20 degrees (Kelafant and others, 1988). The folds are dissected and eroded and best exemplified by Negro Mountain, Laurel Hill, and Chestnut Ridge (Figure 5). In some cases, the coal beds deepen within a short distance of outcrop; in other cases, folds bring the coal beds to the surface, thus causing the gas to be lost by updip migration over time (Adams and others, 1982). Examples of this are the coals that lie near the Chestnut Ridge and Laurel Hill anticlines (Figure 5).

Natural Fracture Systems

The flow of methane through the coal depends on the degree of fracturing because joints and faults, where they are open and extensive, are highly permeable. According to Diamond, Elder, and Jeran (1986, p. 30), "permeability is frequently related to fracture spacing; the closer the fracture spacing, the higher the permeability." However, movement along a fault zone may heat and compress the coal, which decreases permeability (Diamond, Elder, and Jeran, 1986).

Thermal History and Rank

Coal rank increases from northwest to southeast across the Northern Appalachian coal basin (Figure 3). The higher rank coals, the medium- and low-volatile bituminous coals, are located in an area affected by tectonic stresses. Consequently, the coals were subjected to a higher pressure-temperature regime related to depth of burial and metamorphic processes than the high-volatile A bituminous rank.

The thermal maturity (rank) and methane content of a coal bed are determined by time-temperature relationships and former depth of burial. Pressure controls on volume, pore, and moisture reduction are introduced during the initial stages of coalification (Ulery and Puglio, 1984). In the later stages of coalification, temperature and length of time of heating become more significant. The degree of thermal maturity is measured by the vitrinite reflectance value (Figure 9). A study by Ulery (1988), and other studies on petrography and reflectance, proved that reflectance is one of the indicators of methane content. Reflectance values, roof lithology (Appendix 5), and structural position may indicate methane content better than just depth and maceral composition of the coal bed do.

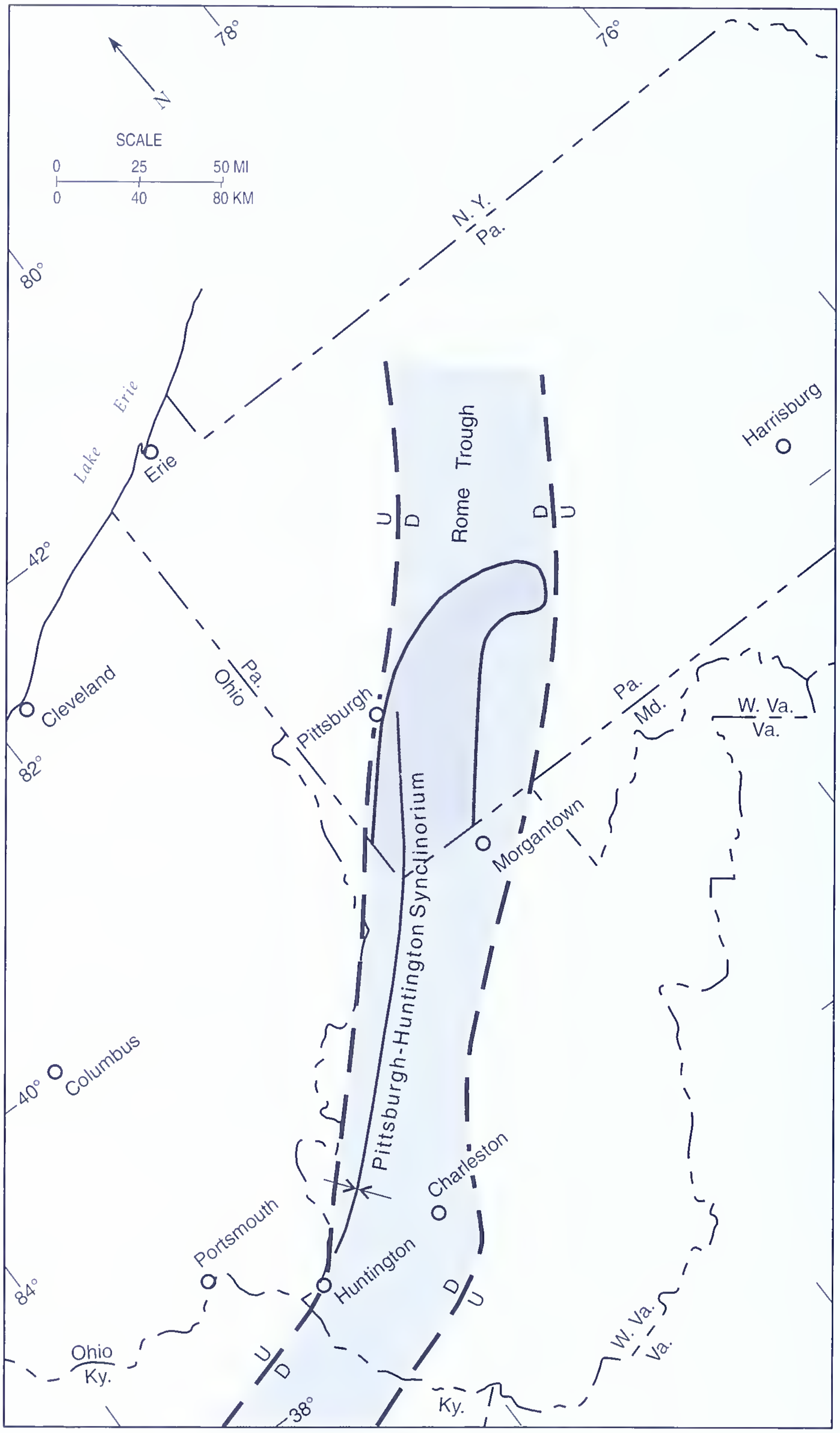

Figure 11. Axis of the Pittsburgh-Huntington synclinorium and study area (dark shading) within the Rome trough (light shading) (modified from Bruner and others, 1995).

According to the results of petrographic and chemical analyses from Ulery (1988), coals that exhibit the highest total gas contents, that is, coals that have gas contents greater than 6.0 cc/g (192 cf/t) (mineral-matter-free basis), where gas content values range from 1.1 to 10.6 cc/g (35 to 340 cf/t), are the Waynesburg, Uniontown, Pittsburgh, Brush Creek, Mahoning, Upper Freeport, Upper Kittanning, Middle Kittanning, Brookville, and Mercer. These results are based on total vitrinite percentage and mean-maximum reflectance percentage.

Depositional and Stratigraphic Controls

Regionally, the depositional record indicates that the coals of the Northern Appalachian coal basin occur over a large area. Bruner and others (1995), however, concluded that the Pittsburgh seam is thick and laterally continuous, but Allegheny and Pottsville Formation coals are generally thinner and less continuous than the Pittsburgh. Locally, the continuity of the coals is disturbed by the presence of clay veins (clastic dikes) and channel sandstones and is governed by the physical limits of the former coal swamp.

Channel sandstones are cut-and-fill features that were formed by ancient streams and later filled with sediment. These features not only are a hindrance to mining but can also block the flow of methane (Diamond, Elder, and Jeran, 1986). The hardened clay and silt wedges of clay veins can penetrate coal beds and cause discontinuities that affect methane emissions (Diamond, Elder, and Jeran, 1986). They also form cells that may contain anomalously large volumes of gas isolated under local high pressure. In addition, in Fayette, Greene, and Indiana Counties, the possibility of abnormally high gas contents and coal rank exists because of contact metamorphism caused by igneous dikes (Adams and others, 1984).

Hydrogeologic Controls

In order to design a gas-development field or maximize the productivity of a gas well, knowledge of the hydrogeologic properties of coal beds is important. Hydrogeologic characterization is especially advantageous for water-saturated or near-saturated coal beds. CBM reservoir pressures are mainly governed by groundwater hydrostatic head. Coals above drainage or coals that crop out have lost most of their gas. Highly permeable coal beds must be dewatered first before any significant gas flow by desorption can occur, because the methane is adsorbed on the surface of the coal and bound by reservoir pressure (McKee and others, 1984). To avoid problems caused by excess water, aquifers should either be avoided during the stimulation process, or site-specific surface casing should be provided to avoid caving and water influx.

METHANE DRAINAGE RECOVERY TECHNIQUES AND CURRENT PROGRAMS

Drainage methods used in Pennsylvania include vertical (vertical pre-mine) boreholes, gob wells (vertical gob), and horizontal (horizontal pre-mine) boreholes. In most cases, CBM wells require special drilling or completion techniques to connect the reservoir effectively to the well bore. Vertically drilled wells are most common and can be drilled into the coal bed several years in advance of mining. Completion techniques range from hydraulic fracturing of wells that have casings to open holes, some having enlarged cavities. Since Pennsylvania coals have low permeability, most wells use artificial stimulation. Localized reservoir characteristics such as rank, pressure, permeability, and gas content must be considered for each well completion. Vertical wells typically produce gas of more than 90 percent purity.

Gob wells, which are becoming more popular in Pennsylvania, are drilled from the surface to a point 10 to 50 feet above the target seam prior to mining (Bibler and others, 1997). As longwall mining advances under the well, the gob or coal and surrounding strata above the coal collapse; this introduces methane-charged strata into the area around the well. Methane then flows from the gob into the gob well and to the surface. Gas quality is initially almost pure methane; however, over time, additional mine air can flow into the gob area and dilute the methane. The heating value of gob gas ranges between 300 and 800 Btu/cf (Bibler and others, 1997). Envirogas Recovery, Inc., and CBE, Inc., are operating a gas-enrichment and sales project at the Blacksville No. 1 (closed, although gob gas is being extracted from the mine) and Blacksville No. 2 mines in south-central Greene County (Bibler and others, 1997). Entry portals to these mines also extend into West Virginia, and plans are to expand into the Humphrey No. 7 and Loveridge No. 22 mines, but most of the gas is produced in Pennsylvania (U.S. Environmental Protection Agency, 2000). The four mines are owned by Consolidation Coal Company. Some of the gas recovered meets pipeline specifications without enrichment; consequently, in 1997, mines began selling the gas for direct pipeline use. The enrichment project consists of treating medium-quality coal-mine methane to increase the volume of marketable gas. Carbon dioxide, oxygen, nitrogen, and water vapor are removed from the coal-

Table 2. *Emissions, Heating, Production, and Quality Data for Coal-*

County	Mine	Company	Electric utility supplier	Mining method	Coal bed	Seam thickness (feet)	Sulfur (percent)	Sulfur rating	Ash (percent)
Cambria	Cambria No. 33	BethEnergy mines	Pennsylvania Electric Co.	Longwall	Upper and Lower Kittanning	3.5	0.71–2.05	Low to medium	—
Greene	Bailey	CONSOL	West Penn Power Co.	do.	Pittsburgh	5.2–6.0	1.03–2.41	Medium	—
do	Cumberland	Cyprus Amax	do.	do.	do.	6.5–7.0	1.59–2.62	Medium to high	8.48
do.	Dilworth	CONSOL	do.	do.	do.	6.3–6.6	1.50	Medium	—
do.	Emerald No. 1	Cyprus Amax	do.	do.	do.	6.0	.83–3.65	Low to high	7.55
do.	Enlow Fork	CONSOL	do.	do.	do.	5.7–6.0	1.00–2.41	do.	—
do.	Warwick	Duquesne Light Co.	Duquesne Light Co.	do.	Sewickley	5.2	1.48–2.29	Medium	[3]11
Indiana	Tanoma	Tanoma Mining Co.	do.	Room and pillar	Lower Kittanning	N/A	.85	Low	[3]12.4
do.	Urling No. 1	Rochester and Pittsburgh Coal Co.	do.	do.	Lower Freeport	N/A	.70–1.58	Low to medium	—
Somerset	Grove No. 1	Lion Mining	Pennsylvania Electric Co.	do.	Upper Kittanning	N/A	1.50	Medium	—
Washington	Maple Creek	Maple Creek Mining	West Penn Power Co.	Longwall	Pittsburgh	5.3	1.16–2.10	Medium	—
do.	Mine 84	Eighty Four Mining	do.	do.	do.	7.5	1.33–1.76	Medium	6.5
Total									

[1] Bibler and others, 1997, Table 6–6, p. 6–8, and section "Profiled Mines" for Pennsylvania.

[2] Closed in 1994.

[3] Values are approximate selling percentages.

[4] Closed in 1988, reopened in 1990.

mine methane using amine, catalytic, cryogenic, and conventional molecular sieve processes (U.S. Environmental Protection Agency, 2000). The enrichment project involved processing about 5 MMcfd of gas having a methane content prior to enrichment of about 60 to 70 percent (U.S. Environmental Protection Agency, 2000). The number of coal-mine methane source wells (gob wells) continues to increase where feasible.

Horizontal (400 to 800 feet long) and longhole horizontal boreholes (more than 1,000 feet long) are drilled inside the mine and drain methane from unmined portions of the seam or from blocked-out longwall panels shortly before mining (Bibler and others, 1997). Several hundred boreholes may be drilled within a single mine and connected to an in-mine vacuum piping system that can transport methane to the surface for use instead of yielding wasted emissions. According to the U.S. Environmental Protection Agency (1990), the recovery efficiency of this technique is low, approximately 10 to 18 percent methane; however, the heating value can be greater than 950 Btu/cf (U.S. Environmental Protection Agency, 1991).

According to Bibler and others (1997), 6 out of 12 profiled deep mines (potential candidate mines for methane recovery-and-use projects and those that initiated recovery and use) in Pennsylvania reported the type of drainage method used. Greene County had five vertical gob wells, one vertical pre-mining borehole, and two horizontal pre-mine boreholes; Cambria County had one vertical gob well and one horizontal pre-mining borehole (Table 2). Table 2 also lists CBM production and ventilation data for these mines.

RAG Cumberland Resources LP (formerly Cyprus Cumberland Resources Corporation) instituted a CBM recovery program to test the feasibility of CBM extraction to reduce mining delays. This program is an outgrowth of a pilot study that began in the 1970s and continues to be successful today because of proven cost effectiveness in dramatically reducing mining de-

Mine Methane From 12 Profiled Deep Mines in Pennsylvania in 1996[1]

Btu lb of coal produced	Coal production for 1996 (MM tons)	Estimated ventilation emissions (MMcfd)	Estimated methane drained (MMcfd)	Estimated total methane liberated (MMcfd)	Estimated specific emissions (cf t)	Estimated current drainage efficiency (percent)	Drainage system used	Btu value of recovered methane Btu value of coal produced based on 40% recovery (percent)	Btu value of recovered methane Btu value of coal produced based on 60% recovery (percent)
12,300	0.0	0.0	0.0	0.0	0.0	[2]0	Formerly vertical gob, horizontal pre-mine	9.1	13.6
13,200	7.5	4.9	3.3	8.2	399.5	40	Vertical gob	.6	.9
14,039	5.2	9.3	1.6	10.9	768.0	15	Vertical pre-mine, vertical gob, horizontal pre-mine	1.1	1.6
13,200	4.8	2.5	1.7	4.2	314.1	40	Vertical gob	.5	.7
13,200	3.2	5.8	3.9	9.7	1,092.0	40	Vertical gob, horizontal pre-mine	1.7	2.5
13,000	8.7	8.6	5.7	14.3	599.8	40	Vertical gob	.9	1.4
13,200	1.9	1.1	.0	1.1	213.6	[4]0	—	.3	.5
13,800	.6	.9	.0	.9	588.7	0	—	.9	1.3
12,800	.9	.9	.0	.9	633.0	0	—	.6	.9
12,500	.5	.1	.0	.1	78.5	0	—	.1	.2
13,300	3.4	.7	.0	.7	125.2	0	—	.1	.2
13,100	3.0	4.1	.0	4.1	494.6	0	—	.8	1.1
	39.7	38.9	16.2	55.1					

lays. In a case study by Reese and Reilly (1997), the authors explained that the main purpose of the pilot program of the 1970s was to measure the effects of stimulation treatments and horizontal boreholes on the removal of methane in developmental longwall sections in the Cumberland mine near Waynesburg in Greene County. According to a presentation by Joanne M. Reilly (RAG Cumberland Resources LP) at the April 1997 North American Coalbed Methane Forum in Pittsburgh, two vertical boreholes were converted into gob ventilation boreholes for extraction of methane from the Pittsburgh seam. In an update at the April 1999 session of the same forum, Reilly reported that four vertical boreholes underwent hydraulic fracture stimulation. Methane recovery rates were as high as 143,000 cfd (Joanne M. Reilly, personal communication, 1999). Nine horizontal boreholes drilled parallel to development entries and four surface-to-in-mine boreholes drilled to pipe excess methane to the surface were also completed. “Methane from the long horizontal boreholes drilled parallel to the development entries while of short duration can be significant with sustained rates four months after completion measured as high as 170,000 cfd” (Joanne M. Reilly, personal communication, 1999). By combining hydraulic stimulation of vertical boreholes with horizontal boreholes, the methane stress is relieved at the section development face, thus significantly decreasing the amount of company downtime. By May 1999, one vertical hole was converted to a pre-mining gob ventilation borehole. At this writing, drilling is continuing on three horizontal boreholes per longwall panel (Joanne M. Reilly, personal communication, 2000).

According to Brian N. Shaffer (personal communication, 2000), RAG Emerald Resources LP has an ongoing project at the Emerald mine, also near Waynesburg, which involves drilling horizontal boreholes for degasification prior to mining and vertical boreholes for ventilation of the gas to the surface. The RAG Cumberland Resources LP Cumberland mine initially had two vertical pre-mine wells that are being converted to gob wells, in addition to five longhole horizontal pre-mine wells having a typical length of 4,500 feet. Both companies plan to continue their vertical- and horizontal-well pilot program because it is proving to be effective in reducing excess methane in the mines.

COMMERCIAL POTENTIAL AND ENVIRONMENTAL CONSIDERATIONS

Optimum criteria for locating favorable drilling sites for CBM development in Pennsylvania include the following:

1. Numerous, relatively thick, high-rank coal beds (having a minimum of 1 foot in thickness if part of a multiseam project); however, one or two seams may be just as economic, depending on their gas content.
2. Sufficient gas content within an individual coal bed or from multiple-seam completions, from approximately 125 to 150 scf/t (usually known from areas of extensive mining).
3. A minimum depth of 500 feet.
4. Favorable geologic structure and porosity, and permeability ranging from 0.1 to 0.5 md. Fracture permeability is useful in determining the degree of well-drainage radius; permeability is more favorable on the flanks of anticlines or synclines, where the orientation and degree of jointing are more evident than on the structural axes.
5. Sufficient reservoir pressure (from 125 to 175 psia) and gas saturation.
6. Stratigraphic traps to maintain reservoir integrity and minimize ambiguities in source-rock identification for ownership issues.
7. Significant distance from the outcrop or active mining of a target seam to avoid loss of methane; for production and development, according to William P. Diamond (personal communication, 1992), it is generally advised that a drilling project be located at least 2,000 to 3,000 feet from an active mine.

In general, maximum gas production can be achieved after the typically water-saturated-reservoir pressure is reduced and the coal bed is dewatered, which allows the coal to release free gas. Unlike conventional natural gas reservoirs where the gas occurs in pores in the rock, CBM is an unconventional gas where the methane is adsorbed in micropores or on the internal surface of the coal (Figure 10). CBM wells experience a dramatic increase in production after a sluggish start, resulting in a negative decline curve. After careful analysis, Petroleum Information Corporation (1986) recognized that normal depletion of wells can also occur. The average economic lifespan of a CBM well is about 35 to 40 years (Cervik, 1969).

Degasification can have a significant positive effect on mining activities. Immediate benefits to the mining community include decreased risk of methane explosions, increased productivity, and reduced costs. As an energy source, CBM rivals conventional natural gas in composition and heating (calorific) value, and lacks nuisance gases such as carbon monoxide, sulfur compounds, or nitrogen oxides. In some cases of natural gases (including CBM) having high carbon dioxide, blending with a gas of high heating value or using an adsorption trap will overcome this problem. Average heating values are about 1,000 Btu/cf, but range from 850 to 1,050 Btu/cf (Petroleum Information Corporation, 1986). CBM applications are the same as conventional natural gas applications, as follows: (1) direct addition to natural gas pipelines; (2) use as a boiler fuel in gas turbines to generate electricity (Kim and Deul, 1986; U.S. Environmental Protection Agency, 2000); (3) use as a chemical feedstock for methanol, ammonia, and other chemicals; (4) use as a raw material for the production of liquefied natural gas and gas products (Kim and Deul, 1986); (5) on-site applications; and (6) local use (fuel for local industries) (U.S. Environmental Protection Agency, 2000).

GEOLOGIC FRAMEWORK

According to Edmunds (1999a), approximately 15,000 square miles of the state are underlain by coal beds. The major coal-bearing units, from oldest to youngest, are the Pennsylvanian-age Pottsville and Allegheny Formations, the Conemaugh and Monongahela Groups, and the Pennsylvanian- and/or Permian-age Dunkard Group in the bituminous fields, and the Pennsylvanian-age Pottsville and Llewellyn Formations in the Anthracite region (Figures 7 and 8). Although most of the coals in the basin are only locally continuous, some seams, such as the Pittsburgh coal, are regionally continuous because they formed during incredibly long-term swamp conditions resulting from nearly total lack of sediment input and slow subsidence rates over a large area.

LITHOSTRATIGRAPHY AND COAL-BEARING UNITS

Western Pennsylvania

In western Pennsylvania, the coal-bearing rocks of the Pennsylvanian and Permian Systems are divided into five stratigraphic formations or groups. These are the Pottsville and Allegheny Formations, and the Conemaugh, Monongahela, and Dunkard Groups (Figure

7). Based on coal analyses, western Pennsylvania coals are primarily high-volatile A bituminous in rank and are secondarily medium- and low-volatile bituminous coals in the eastern part of the Main Bituminous field (Figure 3). Cumulatively in western Pennsylvania, about 2,500 to 3,000 stratigraphic feet is commonly preserved in the rock record. (See Figure 3 for the locations of the counties mentioned below.)

Pottsville Formation

The Pottsville Formation ranges from 20 to 250 feet thick in western Pennsylvania (Edmunds and others, 1999). The top is defined as the base of the Brookville coal (Figure 7) (or the top of the Homewood Sandstone). The bottom is marked by a regional disconformity, where Pennsylvanian-age rocks cut down through successively older rocks northward. Throughout much of the southern and central parts of Pennsylvania's coal region, Pennsylvanian-age rocks sit on Mississippian Mauch Chunk Formation "red beds," which are composed of red- and green-colored shales (commonly containing concretionary carbonates) and gray to greenish-gray sandstones. In the north, the disconformity abruptly cuts deep down section in a relatively short distance, so that Pennsylvanian-age rocks are overlying in turn northward the Burgoon Sandstone, then the nonmarine Huntley Mountain Formation and its western, marine counterpart, the Waverly Group (Edmunds, 1996). It is difficult to identify the top of the Pottsville because of the commonly indistinguishable character of the Brookville coal and its surrounding rocks (Viktoras W. Skema, personal communication, 2000). The upper contact is usually determined by calculation, using an established distance down from some of the Lower Allegheny Formation key beds, such as the Vanport Limestone. Recognizing the unconformable base can be even more difficult in cases where the basal Pottsville sandstones are in contact with underlying Mississippian-age sandstones.

The Pottsville is laterally extensive, dominantly nonmarine sandstone and conglomerate, and includes intervals of siltstone, shale, and thin, erratic coals (Edmunds and others, 1979). Skema and Lentz (1994) noted that marine and brackish fossil-bearing shales are also present but are very discontinuous and consequently unreliable as correlation tools. The upper part of the sequence, 20 to 80 feet thick, contains the Mercer coals and associated rocks, including several marine limestones near the Ohio border; fluvial sandstones dominate the lower part of the 0- to 175-foot sequence (Edmunds and others, 1979). In the northern part of the state, these sediments were derived from earlier Paleozoic strata in the northern highlands and the Precambrian rocks of the craton, whereas southern deposits derived from the orogenic belts to the south and east (Meckel, 1967). A significant amount of relief developed on the erosional surface at the Mississippian-Pennsylvanian boundary, greatly affecting subsequent Pottsville depositional patterns (Viktoras W. Skema, personal communication, 2000). In the northwestern part of Pennsylvania, coarse quartz conglomerate and sandstone were formed in fluvial channels emanating from the highlands of northern New York and Canada. These form the Sharon and Olean conglomerates and account for some of the thickest sections of Pottsville found in western Pennsylvania. In west-central Pennsylvania, cuestalike ridges developed on the erosional surface within the Mississippian Mauch Chunk and Burgoon Sandstone outcrop belts. Their effect on upper Pottsville sedimentation was considerable. These paleotopographic high areas remained subaerially exposed well into the Middle Pennsylvanian. Consequently, they did not receive much of the Pottsville sediments being deposited regionally, and instead became sites of lateritic paleosol development that formed the high-alumina Mercer flint clays (Edmunds and Berg, 1971). These areas contain very thin Pottsville to no Pottsville section (Skema and others, 1998; Smith and Skema, 1999).

The Sharon coal is a channel coal that occurs sporadically and is best known in northwestern Pennsylvania. It developed in the south-flowing fluvial channels originating in the northern highlands. The coal varies in thickness from a few inches to about 4 feet, but it is erratic in areal extent and is commonly cut out by channeling (Brant and DeLong, 1960). The Quakertown and Upper and Lower Mercer coals have been locally mined but do not have adequate thickness, areal distribution, or quality to be considered economically significant regionally. Flint (1965) recognized the Mercer in Somerset County to have multiple benches several feet thick at some localities and a single bed 1 foot thick at others. In general, the Pottsville coals can be characterized as being of limited lateral extent and variable thickness. The Sharon and Quakertown coals in the lower half of the Pottsville are especially discontinuous, of very limited extent, and generally very thin. The Mercer coals, though generally thin and commonly split, appear to have significantly more continuity than the coals below.

CBM potential is not significant for Pottsville Formation coals, although the Mercer has displayed minor potential according to the Methane Recovery from Multiple Coal Seams Project at Waynesburg College and Ulery (1988). More exploration is needed to verify the CBM resource potential of this formation.

Allegheny Formation

The Allegheny Formation is about 270 to 330 feet thick and has no apparent regional trend in thickness variation (Edmunds and others, 1999). The upper boundary is marked by the top of the Upper Freeport coal, and the bottom is defined by the base of the Brookville coal (Figure 7). The formation is an interbedded and repeating succession of coal, shale (marine or nonmarine), sandstone, and underclay (some having associated nonmarine limestone), and has numerous variations. Marine units occur in the lower half of the formation below the Upper Kittanning coal, and nonmarine limestones, with rare exceptions, occur at or above that unit (Edmunds and others, 1999). In the Allegheny County area, this group contains three members, the Clarion, the Kittanning, and the Freeport. In general, the Allegheny Formation contains seven regionally persistent coal beds: Brookville (A), Clarion (A'), Lower Kittanning (B), Middle Kittanning (C), Upper Kittanning (C'), Lower Freeport (D), and Upper Freeport (E) (Figure 7).

Coals in the lower half of the Allegheny Formation formed in coastal and distributary-delta swamps. Those in the upper half of the formation developed in alluvial plain, interdistributary flood-basin swamps. The general fluvial nature of the Allegheny Formation is characterized by coalescing, lenticular sandstone bodies having sharp lower contacts and multiple scour surfaces (Bruner and others, 1995). Regional transgressions periodically created shallow, southwest- to northeast-trending marine embayments.

The seven coals in the Allegheny Formation can best be described as coal zones. Each zone may contain a single, continuous bed, a group of closely related individual lenses, or a multiple-bed complex in which the various beds can be separated by tens of feet or merge into a single thick coal (Edmunds and others, 1999). The Upper Freeport coal has been the leading producer within the Allegheny Formation and is second only to the Pittsburgh as a valuable coal. It is about 600 to 800 feet below the Pittsburgh coal. According to Adams and others (1984), the Upper Freeport can range from 2 to 10 feet thick and is known locally in the Allegheny-Butler-Westmoreland County border area as the "Thick Freeport." It is commonly split into two or more benches by clay shale partings. Southward in Allegheny and Westmoreland Counties, and in Fayette, Washington, and Greene Counties, the Upper Freeport coal becomes discontinuous, existing as separate islands having thick coal in the centers that thins toward the margins (Sholes and others, 1979; Skema and others, 1982). Average gas contents for the Freeport coal zone are in excess of 100 cf/t (Adams and others, 1984).

Another coal that is valuable to mining is the Lower Freeport; however, it is variable in thickness. It is best developed in Cambria, Clarion, Clearfield, and Jefferson Counties and along the northeastern boundary of the basin (White, 1891). White also concluded that the Lower Freeport is sometimes separated into two or three benches in Jefferson and Clearfield Counties. It is thin and irregular, and in large areas it is missing southward and westward in the aforementioned counties. Ashley (1928) contended that there may be several closely overlapping coal horizons in the stratigraphic interval located 30 to 65 feet below the Upper Freeport coal. White (1891, p. 161) noted that "the Lower Freeport coal is in the vicinity of Fairmont, Clarion County, Pennsylvania, where according to Chance it is 5 to 7 feet thick without any partings, and furnishes an excellent quality of gas coal, as it does in the Reynoldsville region of Jefferson County."

The Upper Kittanning coal is also important in the Main Bituminous field. It has been mined throughout most of the Main Bituminous field with the exception of the westernmost counties and into northern West Virginia. Sholes and Skema (1974) noted that the coal reaches an average thickness of 4.5 feet in several counties along the northern part of the basin. White (1891) listed the Upper Kittanning as important to mining in Jefferson, Clearfield, Cambria, and Somerset Counties. In Fayette and Somerset Counties, it is double-benched and has a 3- to 4-foot parting. However, according to James R. Shaulis (personal communication, 2000), the Upper Kittanning is rarely double-benched in the northern part of Somerset County. Limited data in Fayette County also suggests that the Upper Kittanning is not commonly double-benched, and Shaulis (1985) showed that not much mining of the seam has occurred in Fayette County. In Fayette, Westmoreland, and Somerset Counties, average methane contents for the Kittanning coal zone are in excess of 300 cf/t (Adams and others, 1984).

The Middle Kittanning is widespread and multiple-bedded across the Northern Appalachian coal basin. In Fayette and Somerset Counties, it is thin, of poor quality, and commonly absent (Flint, 1965; Hickok and Moyer, 1940).

The second most persistent and economic coal seam for mining and more recently for CBM in the Allegheny Formation is the Lower Kittanning. Its thickness ranges from 2.5 to 4 feet in much of western Pennsylvania (Averitt, 1975), but locally the coal thickens to as much as 8 feet in parts of northern Somerset County. In Fayette County, mining has not been extensive on the Lower Kittanning (Shaulis, 1985). White (1891) noted that the Lower Kittanning is split into several divisions. This is especially true in eastern Clearfield County, where five splits of the Lower Kittanning have been mapped (Edmunds, 1968; Glass, 1972).

The Clarion coal and particularly the Brookville coal are commonly split into multiple benches separated by numerous shale partings and, in places, are split into seams separated by tens of feet. Throughout most of Pennsylvania, the Clarion coal is generally present but thin, rarely exceeding 4 feet in thickness. It is less persistent than the Brookville. In Clarion County, the Clarion coal attains a local thickness of up to 7 feet. The Brookville ranges from a few inches to 8 feet thick locally (Sisler, 1928), but it is generally not more than 2 or 3 feet thick (Flint, 1965). Coined the "Dirty A" because of its numerous partings, the Brookville is not mined extensively in some areas because of its high ash content. It is found throughout the southern part of the Main Bituminous field in the state except where it has been eroded, as along the Laurel Hill and Chestnut Ridge anticlinal axes (Adams and others, 1984). According to Flint (1965), the identification of the Brookville in Pennsylvania is questionable, even in its type area. In Somerset County, it is locally thin, nonpersistent, and difficult to trace. In Fayette County, it ranges from 3 to 6 feet thick and is split by clay and bone partings (Hickok and Moyer, 1940). According to James R. Shaulis (personal communication, 2000), the Brookville commonly consists of a 3- to 5-foot zone made up of numerous thin, coaly layers or a single bed up to 3 feet thick. It is not persistent in Fayette County and eastern Somerset County, but is laterally more persistent and thicker in the western part of Somerset County, having a single bed ranging from 3 to 5 feet thick. Based on the lack of direct evidence of mining of the Brookville, Shaulis (1985) illustrated that little mining of the seam has occurred in Fayette County.

There presently is commercial production of CBM from Allegheny coals in Indiana County and from gob gas wells in Cambria County.

Conemaugh Group

By the Middle to Late Pennsylvanian, rapid pulses of a series of eustatic marine transgressions from the northwest deposited a series of marine units within the lower-delta-plain sediments. The Conemaugh Group has few important coals, but it contains calcareous and siderite nodules and fracture fillings (siderite helped galvanize the iron industry in the Pittsburgh area), iron-oxide-rich red beds, and red- and green-mottled beds. The Conemaugh varies in thickness from 520 to 890 feet and occurs between the top of the Upper Freeport coal and the base of the Pittsburgh coal (Edmunds and others, 1999) (Figure 7). It consists of the Glenshaw and Casselman Formations. The boundary between the two formations is the top of the Ames marine zone, which marks the change from the lower, partially marine Glenshaw Formation to the upper, mainly nonmarine Casselman Formation.

According to Edmunds and others (1999), the Glenshaw Formation of the lower Conemaugh (Figure 7) is 280 to 420 feet thick and contains seven separate marine zones (four are well developed and regional in extent; the other three are less prominent and local in extent) as well as the nonmarine deposits. A zone of brackish-water fossils found above the Mahoning coal in a core hole drilled in 1981 by the Pennsylvania Geological Survey suggests the presence of an eighth marine zone. The marine deposits consist of silty, calcareous shale and limestone (Flint, 1965; Hickok and Moyer, 1940). Interfingering of marine with nonmarine deposits represents a series of transgressions and regressions of the sea. The Ames marine zone is the youngest and most extensive of the transgressions.

The Casselman Formation of the upper Conemaugh is a 230- to 485-foot thick (Edmunds and others, 1999) clastic sequence comprised of shale, siltstone, sandstone, mudstone, nonmarine limestone, a few red beds, and thin beds of coal (Flint, 1965; Hickok and Moyer, 1940). Various shades of red, green, and gray characterize the dominant siltstones and sandstones. The Casselman represents deposition of fluvial and deltaic sediments along an estuary margin, which heralded the isolation of the Northern Appalachian coal basin (Adams and others, 1984). One or two marine or brackish shale or limestone beds in the lower Casselman Formation mark the last marine transgression of the Paleozoic; they are correlative with the Skelley Limestone and associated intervals of Ohio (Edmunds and others, 1999). Edmunds and others (1999) contended that correlation of individual units in the Casselman is difficult because of large lateral changes in overall thickness and lithologic character, the lack of attention given to this part of the section because it lacks economically important coal and rock strata, and the lack of significant fossil zones or other readily apparent key beds.

Although the group contains numerous coal beds, the coals are thin, erratic, and mostly noncommercial. The Conemaugh is also known as the "Lower Barren Measures" due to the lack of minable and areally extensive coals (Hickok and Moyer, 1940). However, the Mahoning, Brush Creek, and Lower Bakerstown coals attain local minable thicknesses (Flint, 1965; Hickok and Moyer, 1940). White (1891) noted that the Bakerstown reaches 4 feet in thickness in Somerset County. The Mahoning, Brush Creek, and Bakerstown coals may have minor CBM potential (Figure 7).

Monongahela Group

A complete section of the Monongahela Group from the western boundary of Pennsylvania to western Fayette County is about 270 to 400 feet thick (Edmunds and others, 1999). The upper boundary is marked by the base of the Waynesburg coal and the lower boundary by the base of the Pittsburgh (Figure 7). The Monongahela is composed of the Pittsburgh and Uniontown Formations, separated by the base of the Uniontown coal. The Pittsburgh Formation is distinguished by the laterally persistent and thick Pittsburgh coal and an elongate sandstone body up to 80 feet thick and several miles wide; the Uniontown Formation is marked by thin-bedded sandstones and channel-fill sandstones (Edmunds and others, 1999). Dominant lithologies in the Monongahela Group in most of southwestern Pennsylvania, with the exception of the relatively small sandstone paleochannel overlying the Pittsburgh coal, are limestones and dolomitic limestones, calcareous mudstones, shales, and thin-bedded siltstones and laminites, deposited in a low-energy environment (Edmunds and others, 1999). Coals occupy only a very small part of the group and include the following minable coals: Morantown, Pittsburgh, Blue Lick, Redstone, and Sewickley (Figure 7), which are lacustrine and delta margin in origin. Most of these coals are shallow and low in gas content. The Uniontown coal is 3 feet thick or less in Washington and Fayette Counties, thinning to the south and southwest, and in Greene County it rarely exceeds 1 foot in thickness (Adams and others, 1984). The most laterally extensive of the coals are the Pittsburgh and Sewickley (Viktoras W. Skema, personal communication, 2000).

According to Ashley (1928), the Sewickley generally is thin (4 to 8 inches) but thickens to 5 to 6 feet in southwestern Greene County. In Fayette and Somerset Counties, it averages 2 feet (Flint, 1965; Hickok and Moyer, 1940). Hickok and Moyer (1940) noted an upper and lower Sewickley. The Redstone coal reaches a thickness of 3 to 5 feet in southwestern Pennsylvania (Headlee and Nolting, 1940), but it is absent in much of Washington and Greene Counties. The Redstone and Sewickley coals are relatively shallow and are not expected to be commercial; only a small area has coal having a gas content greater than 100 cf/t (Adams and others, 1984). Although significantly mined out, the Pittsburgh coal is still economically important to mining and accounts for more than 60 percent of the bituminous coal production of Pennsylvania (Pennsylvania Coal Association, 2000). The Pittsburgh is the most extensive and thickest coal in western Pennsylvania, averaging between 6 and 9 feet thick, and ranging from 4 to 12 feet in Greene County; overburden thickness ranges from 200 to 1,200 feet (Kim, 1975). In Washington County, the average thickness of the Pittsburgh is 4.8 feet and thickness ranges from 3.5 to 7.5 feet; overburden thickness ranges from 0 to 760 feet (Kim, 1974). In the type locality in Allegheny County, and similarly throughout southwestern Pennsylvania, with the exception of Somerset County, "the bed is split into a roof and lower bench" (Adams and others, 1984, p. 24). "Generally the bed is double, consisting of a roof division and a lower division, separated by a clay parting 1 inch to 3 feet thick and containing thin bands of coal" (Sisler, 1926, p. 19). The roof ranges from 2 inches to 8 feet thick and usually has a few partings and a high ash content; the coal ("lower bench") ranges from 3.5 to 9 feet thick and is divided into benches by shale and bone partings. Shales in the Monongahela Group can provide impermeable seals to gas migration. Associated geologic discontinuities such as clay veins contribute to locally high emission rates in the Pittsburgh. These features tend to form zones in the coal where isolated pockets of gas are confined under high pressure (Diamond, Elder, and Jeran, 1986).

The Pittsburgh coal is a prime target for CBM because of its continuity, thickness, and high gas contents. Average desorption values from Washington and Greene Counties in Pennsylvania and Marion County in West Virginia range from 122 to 216 cf/t (Adams and others, 1984). It was the main reservoir for numerous test projects of the 1970s. Today, the Pittsburgh is significantly mined out, but in some areas, such as Greene and Washington Counties, gas wells are currently producing CBM from the Pittsburgh gob or caved zone from active and abandoned mines.

Dunkard Group

The Dunkard Group is about 1,100 to 1,200 feet thick at its type locality at Dunkard Creek, Greene County (Ashley, 1928). It is the youngest pre-Pleistocene sedimentary rock unit exposed in southwestern Pennsylvania and lies conformably on the Monongahela Group. The Dunkard also occurs as an erosional remnant in the Appalachian Plateau, which makes it difficult to accurately determine its areal extent and thickness. The group is mostly Permian in age, but the lowest unit, the Waynesburg Formation, is considered to span the Pennsylvanian/Permian boundary (Barlow and Burkhammer, 1975) (Figure 7). The Dunkard contains shale, shaly sandstone, claystone, nonmarine limestone, and thin, erratic coals. These coal beds, with the exception of the Waynesburg, are too thin and discontinuous, and all are too shallow, to have significant gas contents. Cyclic sedimentation in the group was probably caused by a changing center of deltaic deposition and deltaic lake-margin environments (Beryhill and others, 1971; Donaldson, 1969, 1974). According to Adams and others (1984), sea-level changes may have contributed to the widespread distribution of certain marker zones.

The Dunkard Group contains three formations: the Waynesburg, Washington, and Greene. The Waynesburg Formation, 85 to 210 feet thick (thicknesses of all three formations are from Edmunds, 1999b), is defined as the interval from the Waynesburg coal to the base of the Washington coal; it is sandier and has thicker coal beds than the rest of the group (Edmunds, 1999b). The Washington Formation, 160 to 270 feet thick, includes the units from the base of the Washington coal to the top of the Upper Washington limestone; three limestone units mark the top, middle, and bottom of the formation. The Greene Formation extends from the top of the Upper Washington limestone to the present erosion surface; the maximum thickness is approximately 750 feet in southwestern Greene County. The formation is similar in character to the Waynesburg Formation, except that the coals and limestones are not as developed.

The Dunkard contains few persistent mappable units. Some *Lingula* and brackish or marine orbiculoid brachiopods and gastropods were identified in the Elm Grove limestone and Washington coal zone in southern Ohio (Cross, 1975). The presence of various fossil leaves, spores, and pollen throughout the Dunkard Group, and more importantly, from above the Washington coal, suggests a transition from the great Pennsylvanian swamp flora to Permian elements.

The Waynesburg and Washington coals (Figure 7) are the only prominent coal beds in the Dunkard Group, but they are considered poor targets for CBM. The Waynesburg is the youngest coal to produce CBM and has had historic CBM production from conventional wells. The Waynesburg is considered a potential source of methane where it is deeply buried along the axis of the Nineveh syncline (Figure 5). However, due to its high ash content and shallow depth, it is only of local importance. The Waynesburg is primarily high-volatile A bituminous in rank (Headlee and Nolting, 1940). Gas contents for the Waynesburg are approximately 90 cf/t (Adams and others, 1984). In Fayette County, the Waynesburg averages 3.5 feet in thickness and ranges from 5 to 10 feet in thickness; it is characterized and split by a thick parting (Adams and others, 1984). Other minor coals of the Dunkard Group are the Waynesburg "A" and "B," Little Washington, Washington, Washington A, Jollytown, and Ten Mile.

Eastern Pennsylvania

The Anthracite region of eastern Pennsylvania consists of five distinct coal fields: (1) the Northern Anthracite field; (2) the Southern Anthracite field; (3) the Western Northern Anthracite or "Bernice" field (which actually contains semianthracite, is the smallest of the Anthracite fields, and is only of minor economic importance) (Eggleston and others, 1993); (4) the Western Middle Anthracite field; and (5) the Eastern Middle Anthracite field (Figure 3). The region, about 5,500 square miles in area (Wood and others, 1986), is in the Ridge and Valley province and part of the Appalachian Plateaus province of northeastern and north-central Pennsylvania (Figure 4). The fields are located in Carbon, Dauphin, Lackawanna, Luzerne, Northumberland, and Schuylkill Counties and parts of Columbia, Lebanon, Sullivan, Susquehanna, Wayne, and Wyoming Counties. According to Averitt (1975), the region contains 96 percent of the identified anthracite resources in the United States.

Structural Controls and Tectonic History

The Anthracite region is located in a northeast-trending, asymmetrical structural depression. More specifically, it is situated on the "diminishing, east-plunging, first-order folds in eastern Pennsylvania" in "one of the most extensively faulted areas of the entire Appalachian orogen" (Faill and Nickelsen, 1999, p. 276). The coal fields are contained in moderately to deeply downwarped synclinoria separated by complementary anticlinoria. These structures contain complexes of synclines and anticlines broken by many reverse, thrust, and bedding-plane faults originating from one or more décollements under the coal-bearing rocks (Wood and others, 1986).

The Southern field is the most deformed, exhibiting several highly faulted, closely spaced synclinal basins, whereas the outlying semianthracitic fields (Figure 3) are only mildly deformed (Wood and others, 1986). Most of the structural deformation of Carboniferous strata in the Anthracite region occurred during the Alleghany orogeny of Early to Middle Permian and perhaps the Triassic (Wood and others, 1986).

Unusual coal thicknesses were caused by flowage as a result of folding and faulting. Coal thickens to three to four times normal thickness in the axes of synclines. Excessive local thicknesses were created by thrust faults, which dragged less competent coal strata and associated enclosed strata (Wood and others, 1986).

Rank

The strata are intensely folded and faulted, and coals are of the highest ranks. Coal rank increases from semianthracite in the west to anthracite in the east, suggesting either increasing depth of burial (Levine and Davis, 1983), or increasing structural complexity (Wood and others, 1986). Pennsylvania anthracite coal is low in sulfur and has high Btu values and moderately high ash content. Average coal-quality parameters for anthracite from Swanson and others (1976) are 13 percent ash, 0.8 percent total sulfur (mainly organic), and heating values of 12,800 Btu (as-received basis). Higher sulfur values occur in the Northern Anthracite field due to marine influence from the Mill Creek limestone (Deasy and Griess, 1963; Wood and others, 1986).

Depositional History

The Anthracite coal region is contemporaneous with the Pennsylvanian-age Pottsville and Allegheny Formations and the Conemaugh Group, although most commercial anthracite is probably time-equivalent to the Allegheny Formation (Dennison, 1978). The Anthracite region may also be contemporaneous with the Monongahela Group based on the presence of certain identifiable plant fossils in the roof shale of the No. 25 coal bed (Eggleston and others, 1988). Unlike the bituminous coal fields of western and north-central Pennsylvania, the Anthracite region has undergone tremendous tectonic stress during periods of mountain building. Uplift in the southeast provided clastic sediments to the Anthracite region, and continental collisions created massive décollements (Lyons, 1986). After deposition of Pottsville sediments, peat developed in broad interfluve swamps on an alluvial plain accompanied by periodic influxes of nonmarine sediments from streams into the swamps—the precursors of modern coal-bearing sequences (Lyons, 1986). Clastics were deposited as alluvial fans or fine to coarse detritus (Wood and others, 1986). Close to 50 swamps existed over an area of hundreds to thousands of square miles for hundreds of thousands of years. Some of the thicknesses of the anthracite beds strongly suggest that plant growth continued uninterrupted by tectonics for long time periods. Altschuler and others (1983) found that peat accumulation in the Everglades is about 1 foot per 1,000 years. These data and the compression rates of Ryer and Langer (1980) were used to calculate that more than 400,000 years of peat and plant detritus accumulation is required to create a 40-foot-thick anthracite bed.The usual thickness of individual anthracite beds probably does not exceed 60 feet, measured normal to bedding, and most are much thinner (Eggleston, 1993), but even so, these rates imply that the beds were formed over a long period of time.

Pottsville Formation

The Early to Middle Pennsylvanian Pottsville Formation is one of two major coal-bearing units in the eastern part of the state (Figure 8); however, the second one, the Llewellyn Formation, contains thicker and more numerous coal beds. The Pottsville Formation contains six major mined seams in the Southern, Western Middle, and Eastern Middle Anthracite fields and one seam in the Northern Anthracite field. The average thickness of the Pottsville Formation is 50 to 1,500 feet (Wood and others, 1986). It is divided into three members, the Early Pennsylvanian Tumbling Run, the late Early Pennsylvanian Schuylkill, and the Middle Pennsylvanian Sharp Mountain. Average thicknesses of Pottsville coal beds reach up to 10 feet (Lyons, 1986). The Pottsville Formation is a complex unit consisting of about 75 to 90 percent conglomerate and conglomeratic sandstone; the remainder consists of finer sandstone, siltstone and silt shale, claystone, and coal (Edmunds, 1993). Edmunds also reported that the Pottsville conformably overlies the Mauch Chunk Formation in the Southern and Middle Anthracite fields, but is unconformable on the Mauch Chunk and older units in the Northern Anthracite field. The upper contact of the Pottsville conformably underlies the base of the Buck Mountain coal. The formation also contains strata resistant enough to form high ridges around each field (Wood and others, 1986).

Llewellyn Formation

The Middle to Late Pennsylvanian Llewellyn Formation is a thicker, coarser grained equivalent of the Allegheny Formation, the Conemaugh Group, and possibly the Monongahela Group, as suggested by Eggleston and others (1988). The uppermost part of the Llewellyn could be Permian because another 755 feet of strata lies above the No. 25 coal bed in some places, and that bed has been shown to be at least Early Virgilian in age (Eggleston, 1993). The Llewellyn underlies the valley (synclinal) floor of each coal field. The lower part of the formation consists of the following numbers of principal coal beds: 19 in the Northern Anthracite field, 16 in the Southern and Western Middle Anthracite fields, and 14 in the Eastern Middle Anthracite field. The average coal-bed thickness is from 2 to 9 feet (Lyons, 1986). Tectonic folding and faulting have created impressive thicknesses in the Buck Mountain No. 5 at 96 feet and the Mammoth at 50 feet (Lyons, 1986). The extreme local thicknesses of the Llewellyn Formation of 98 feet or more occur where folding and faulting caused mass flow of coal or a doubling of the bed back on itself (Eggleston, 1993).

The Llewellyn extends from the base of the Buck Mountain No. 5 coal, underclay, or shale to the present erosional surface, except where mantled by Quaternary alluvium (Wood and others, 1986). Its maximum thickness reaches about 3,500 feet in the central part of the Southern field (Wood and others, 1986). Similar to the Pottsville Formation in lithologic complexity, the Llewellyn consists of conglomerate, sandstone, siltstone, shale, clay, coal, and minor amounts of marine limestone (Wood and others, 1986). However, conglomerate and conglomeratic sandstone are less common in the Llewellyn compared to the Pottsville Formation. According to Eggleston (1993), Llewellyn clastics may be classified as subgraywackes and are tabular, lenticular, and wedge shaped. Fossilized plant material is common throughout the formation.

From a mining and stratigraphic standpoint, the Buck Mountain No. 5 and its equivalents are important, relatively thick (7 to 10 feet), and widespread over the entire Anthracite region. The Mammoth coal zone and its equivalents (which can occur in three splits in the Southern, Western Middle, and Eastern Middle fields) are also significant, having as much as 65 feet of coal. The Mammoth is up to 50 feet thick where it occurs as one bed. It is used as a marker bed for correlations on drilling logs because of its continuity and unusual thickness.

Coal-Bed Methane Potential

It is nearly impossible to evaluate the methane drainage potential in the Anthracite region of eastern Pennsylvania. Few projects have been initiated here due to the economics of drilling in a region of complex structure and stratigraphy (Diamond, LaScola, and Hyman, 1986; Diamond and Levine, 1981). According to Kim (1977), anthracite coal adsorbs at least twice as much gas as high-volatile bituminous coal at any given depth. Therefore, anthracite estimates were based on the potential recovery of 180 cf/t of gas (Briggs and Tatlock, 1999). Methane contents for anthracite are also known to be either anomalously high or low, but due to a poorly developed fracture system, production rates have been found to be low with or without artificial stimulation. Steeply dipping and distorted coal beds complicate the scenario for favorable commercial development in the Anthracite region. However, the variety of data presented from these sources reveals very high gas contents in localized areas of the Anthracite region. This suggests that further CBM exploration should be conducted in this part of Pennsylvania (Lyons, 1997). New research by RMB Earth Science Consultants Ltd. (1998), who used methane adsorption isotherms, revealed promising results on gas storage capacity for the Buck Mountain ("Big Buck"), Seven Foot, and Mammoth (lower and upper splits) seams of the Pioneer Tunnel tourist mine in Ashland.

STRUCTURE

The extent of deformation in the Appalachian Plateau has been controversial since the 1950s. Early geologists believed in basement involvement in Appalachian folding (Gwinn, 1964). Later studies proposed the "thin-skinned" nature of Appalachian deformation, in which incompetent Silurian rocks were deformed, creating plateau structures such as anticlines and synclines that extend to a décollement surface near the base of the Silurian Salina Group (Beardsley and others, 1999). Another point of debate involved whether strata above the décollement surface were thrust northwestward as an extension of the Ridge and Valley system or slid southeastward on the Salina salt. In the late 1970s, geologists suggested that flow of salt-bearing rock from synclines to anticlines formed most of the structures, whereas others postulated that salt solution and removal was responsible for the Plateau structures (Beardsley and others, 1999). Many problems of Appalachian Plateau structure and tectonics remain to be solved despite the extensive work that has been done on salt tectonics and the existence of new seismic breakthroughs (Beardsley and others, 1999).

Tight to moderate folding interrupts the otherwise flat-lying, undeformed Northern Appalachian coal basin of the Pennsylvania Plateau region (Figures 1, 4, and 5). Few faults are known to exist at the surface of this region (Beardsley and others, 1999). The folds are arcuate and trend northeast to southwest, having dips generally between 10 and 20 degrees (Kelafant and others, 1988). Fold amplitudes generally decrease to the northwest, and Plateau structures disappear in northeastern Pennsylvania. Major axes trend approximately N35°E. In some cases, these folds bring the coal beds to the surface, thus causing the gas to be lost by updip migration over time. Examples of this are the outcrops of Pittsburgh, Upper Freeport, Lower Freeport, Upper Kittanning, and Lower Kittanning along the more steeply dipping flanks of the Chestnut Ridge and Laurel Hill anticlines of Fayette, Westmoreland, Indiana, and Cambria Counties (Sisler, 1926) (Figure 5). Strata on the western edge of the basin, however, are less structurally deformed, and the overburden is thicker.

The deepest part of the Northern Appalachian coal basin, the Dunkard basin, is an area 35 miles wide by 250 miles long containing coals up to 1,500 feet deep (McCulloch, Diamond, and others, 1975) in southwestern Pennsylvania and northeastern West Virginia. Adams and others (1984) reported that some coals have a maximum overburden thickness of about 2,300 feet in Greene County, Pa., and Wetzel and Tyler Counties, W. Va. The deepest depth to the top of a coal bed from Pennsylvania Geological Survey records is 1,735 feet in the Brookville in Greene County (Waynesburg 7.5-minute quadrangle). The relatively high rank, total effective coal thickness, and deep burial of the coal suggest that this area has great potential for production. Coal ranks in the Northern Appalachian coal basin increase from northwest to southeast, and the medium- to low-volatile bituminous ranks fringe the southeastern part of the basin (Figure 3).

Nickelsen and Hough (1958) examined the strike and surface character of more than 6,500 coal and shale joints at 500 localities in the Appalachian Plateau of Pennsylvania. Their observations revealed the following: "(1) regional variations of type of joint in rocks of similar lithology, (2) the relation of joint orientation to other structures, (3) areas where joint orientations in adjacent shales and coals differ" (Nickelsen and Hough, 1958, p. 1624). Major fracture and joint systems in the Northern Appalachian coal basin trend northwest to west-northwest and have a less pronounced north-south orientation (Colton and others, 1981; Kulander and others, 1980; Nickelsen and Hough, 1967). Dominant (face) cleat systems in Pennsylvania trend in a northwest-southeast preferred orientation (Figure 12). This orientation is, in part, in response to coalification and local structural deformation (Kelafant and others, 1988; Ver Steeg, 1942). According to Nickelsen and Hough (1967), face cleats formed in response to small stress differences in the developing paleostress fields prior to folding and faulting. The average face cleat orientation is N67°W, and the average butt cleat is N28°E (Bench and others, 1977; Diamond and others, 1976; McCulloch, Diamond, and others, 1975). According to Diamond, Elder, and Jeran (1986), the results from horizontal drill holes showed that drilling perpendicular to the direction having the highest concentration of face cleats will yield 2.5 to 10 times as much gas as holes drilled at right angles to the secondary or butt cleat. More importantly, the highest permeabilities (directional permeability) providing good gas flow are parallel to the face cleat orientation (Adams and others, 1984; Diamond, Elder, and Jeran, 1986). Soot (1989), however, analyzed production histories for horizontal drill holes in the Pittsburgh seam. He found no conclusive correlation between long-term gas production and orientation of drill hole to face cleats. These studies imply that cleat orientation does, at least, influence the short-term effect on production as observed by the mining industry. Other geologic factors may be more important in designing an effective degasification program for long-term consideration.

COAL-BED METHANE POOLS AND PRODUCTION

At this writing, there are 27 CBM pools in Pennsylvania as recognized by routine well-record processing (Figure 13). Although some of the wells associated with these pools are described in historical and serendipitous accounts of short-term CBM production along with conventional natural gas production, the wells yielded significant open flows from coal beds and are included in this study. As a supplement to the above, a cursory search of gas and dry wells up to 3,000 feet deep in the study area revealed significant gas flows from coal in nine wells in Greene and Washington Counties. A brief summary of the year of well completion, the name of the coal, the depth of the coal, and gas yield for each well is included in Table 3. The table shows that 198 Mcf from the Pittsburgh seam was reported on a 1918 Greene County well record.

The distribution of pools in each county are as follows: 10 in Greene County, 5 in Fayette County, 4 in Westmoreland County, 3 in Washington County, 2 in Cambria County, 2 in Indiana County, and 1 in Allegheny County. There are many conventional and unconventional gas fields and pools in the target area. Commercial natural gas production is high, and there is an existing, compatible pipeline infrastructure to bring the gas to market.

The wells were classified based on their status according to the following general categories: (1) new (active, newly permitted, and not drilled or completed yet [one year is allowed to complete the well]; at various stages of exploration, extraction, or production; production status unknown; well record not received; or well data not entered into state computer system); (2) producing (active, known local or commercial production); (3) nonproducing and/or inactive (no production after one year or not equipped for production within 60 days after completion [inactive status qualifies for a shut-in period of five years, but the operator must demonstrate future well utility]; low, short-term, or unknown production; and not plugged/intend to be plugged); (4) nonproducing, plugged, and/or waiting for plugging certificate; (5) dry and inactive (not plugged); (6) dry and plugged (not equipped for production within 60 days after completion, and opera-

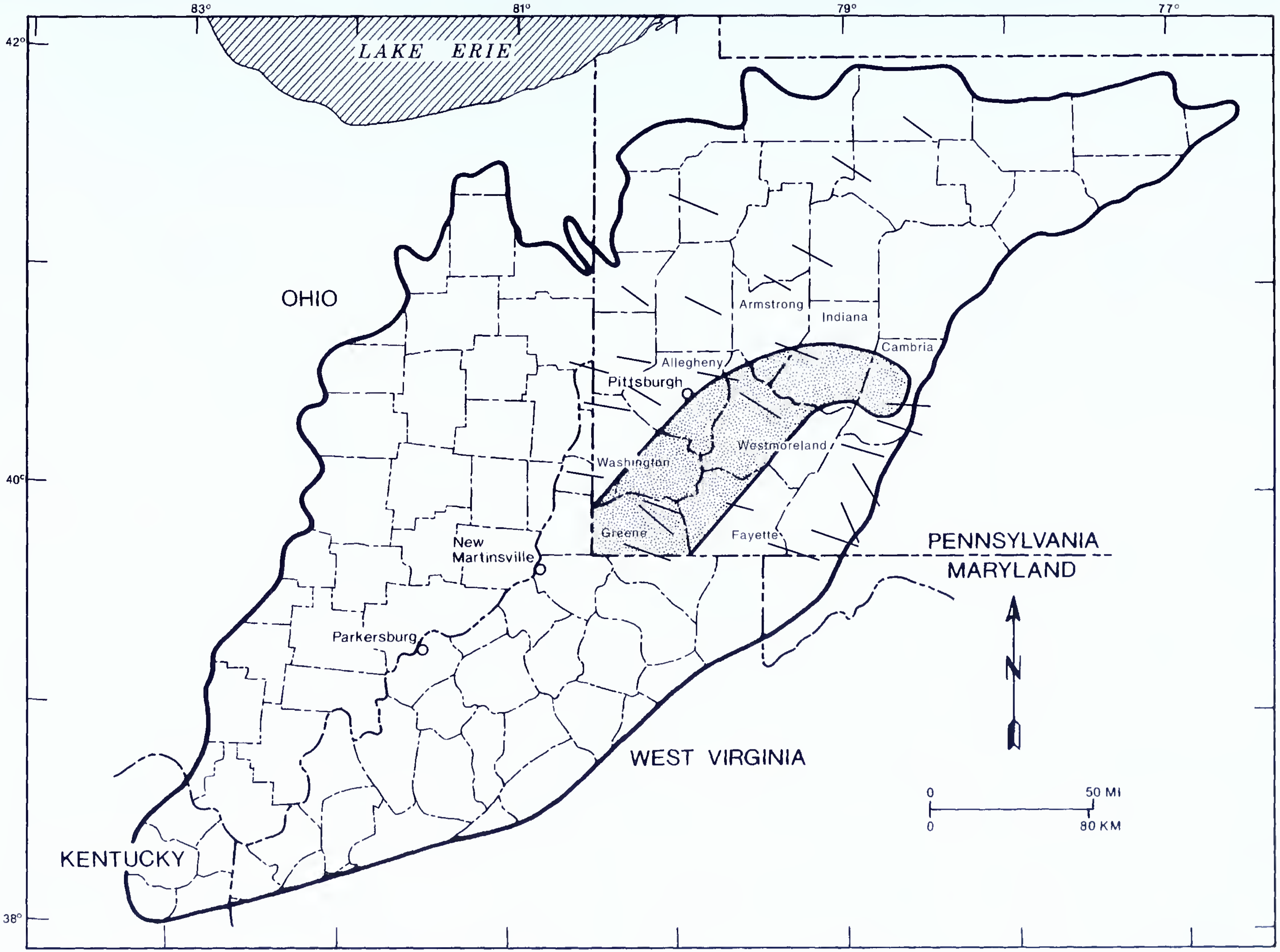

Figure 12. Dominant coal cleat orientations in the Northern Appalachian coal basin (modified from Adams and others, 1982, and Kelafant and others, 1988; some data from Colton and others, 1981).

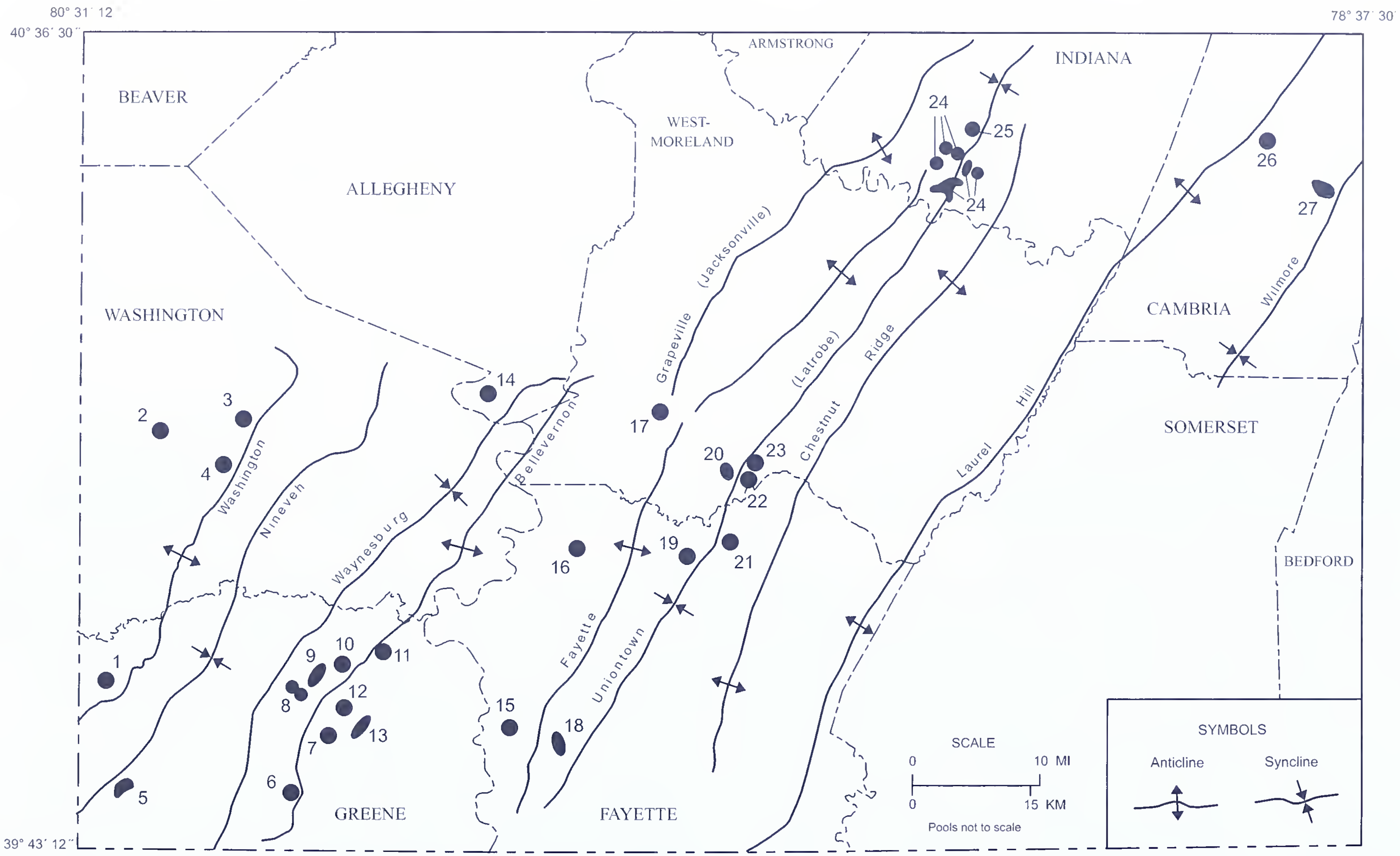

Figure 13. Coal-bed methane pools and fields, and major fold axes in southwestern Pennsylvania; fold axes from Bragonier and Glover (1996), Dodge and Glover (1984), Faill (in preparation), Glover (1990), and Skema (1987, 1988). 1, Dunkard Fork pool, Rich Hill field; 2, Unnamed pool, Mehaffy field; 3, Unnamed pool, Washington-Taylorstown field; 4, South Franklin pool, Lagonda field; 5, Windy Gap pool, New Freeport field; 6, Rudolph Run pool, Gump field; 7, Unnamed pool, Waynesburg field; 8, Blairtown pool, Waynesburg field; 9, Turner pool, Waynesburg field; 10, Poverty Run pool, Pratt storage field; 11, Unnamed pool, Jefferson field; 12, Unnamed pool, Waynesburg field; 13, Frosty Run pool, Waynesburg field; 14, Detwiler pool, Forward field; 15, Unnamed pool, Masontown field; 16, Unnamed pool, Kenneth field; 17, Waltz Mill pool, Oakford field; 18, Smiley pool, Highhouse field; 19, Adelaide pool, Waltersburg field; 20, Morewood pool, Mayfield field; 21, Moyer pool, Mayfield field; 22, Orchard Hill pool, Hoggs field; 23, Ramsay Terrace pool, Armbrust field; 24, Campbells Mill pool, Blairsville field; 25, Unnamed pool, Indiana field; 26, Powell pool, Carrolltown field; 27, Unnamed pool, Munster field.

Table 3. *Significant Gas Flows From Coal Beds in Nine Wells Drilled in Greene and Washington Counties*[1]

Permit number	Year completed	Well type	Coal name	Coal depth (feet)	Gas yield (Mcf)
059–01258	1918	Gas	Mapletown	562–569	151
			Pittsburgh	653–661	198
059–01791	1939	do.	do.	310–317	300
059–20013	1957	Dry	do.	798–805	30–40
125–21551	1926	Gas	Upper Freeport	680	310
125–90059	1948	do.	Freeport	944–947	283
125–20033	1958	do.	Not reported	845	35
125–20126	1964	Dry	Pittsburgh	513–520	30–50 (low grade)
125–20150	1965	do.	do.	720–726	10
125–20124	1965	do.	Not reported	260	250

[1] This list supplements data for the wells described in the "Coal-Bed Methane Pools and Production" section (p. 40). The list is a result of a search for gas wells drilled to depths of up to 3,000 feet.

tor unable to demonstrate future well utility; little or no production); (7) dry and/or junked (abandoned but not necessarily dry or plugged) and/or plugged; and (8) cancelled, expired, and/or not drilled (cancelled by the operator, expired, not drilled within one year of permit issuance). Some of the above include wells originally intended for CBM and having limited or no gas production or only gas shows from coals. These wells have been reclassified as storage wells, core wells (no production, used for study), or shallow wells having conventional natural gas production.

It is difficult to project a realistic count of CBM wells that reflects their dynamic field status. For this report, 228 located CBM wells of varying permit status were documented; this includes data up to January 2000 (Markowski, 2000). By June 2000, approximately 20 more well records were received (this does not necessarily reflect actual field production). Out of the 228, a conservative estimate of 125 wells are producing on a commercial level (based on communication with available operators in addition to the number of well records received). The 228 wells were classified, according to well records received up to January 2000, as follows: 97 new (most of these are probably producing by now); 36 known producing; 24 nonproducing and/or inactive; 23 nonproducing and plugged/waiting for plugging certificates; 19 expired and/or not drilled; 7 cancelled and/or not drilled; 7 dry and inactive; 7 dry and plugged; 3 storage; 2 nonproducing, inactive, intend to be plugged; 1 dry, junked, and plugged; 1 junked and plugged; and 1 nonproducing, core.

The total of 228 represents successful and unsuccessful wells drilled for CBM exploration and production and wells that serendipitously encountered significant open flows of methane and conventional natural gas in Pennsylvania from 1938 to 1998 (Figure 14). These "coal-bed methane wells" consist of the following types: (1) wells penetrating coal beds or gob and having reported gas shows or production; (2) wells converted from pre-mining degasification or ventilation boreholes; (3) wells targeted for the coal beds that did not produce gas from either the coal beds or the associated sandstones (dry holes); (4) wells targeted for the coal beds that produced from associated sandstones; and (5) unsuccessful CBM wells retargeted to deeper, conventional gas reservoirs.

State regulations for spacing of CBM wells are the same as for conventional natural gas wells in a coal area. The spacing requirements are 1,000 feet between wells and not less than 330 feet from the well to the boundary of the tract on which it is located. The first requirement can be reduced to 900 feet if the coal owner approves. According to Commonwealth of Pennsylvania Act 1984–214, the Coal and Gas Resource Coordination Act, the Bureau of Oil and Gas Management can grant an exception from the minimum 1,000-foot spacing "where the vertical distance between the producing formation of the proposed gas well and the producing formation of any other well is 1,000 feet or greater, where the permit applicant and the owner of the workable coal seam consent in writing."

Pools, fields, and associated wells representing historical, serendipitous, and current CBM production from 1938 to 1998, including pilot programs, throughout Fayette, Greene, Allegheny, Indiana, Westmoreland, Cambria, and Washington Counties, are highlighted below in approximate order of discovery and completion within each county. The completion years of the described wells are listed next to the pool and field names in each subheading. Production and interval depths were taken from public well records and completion reports. Additional well details can be found in the *Pennsylvania Coalbed Methane Wells Spread-*

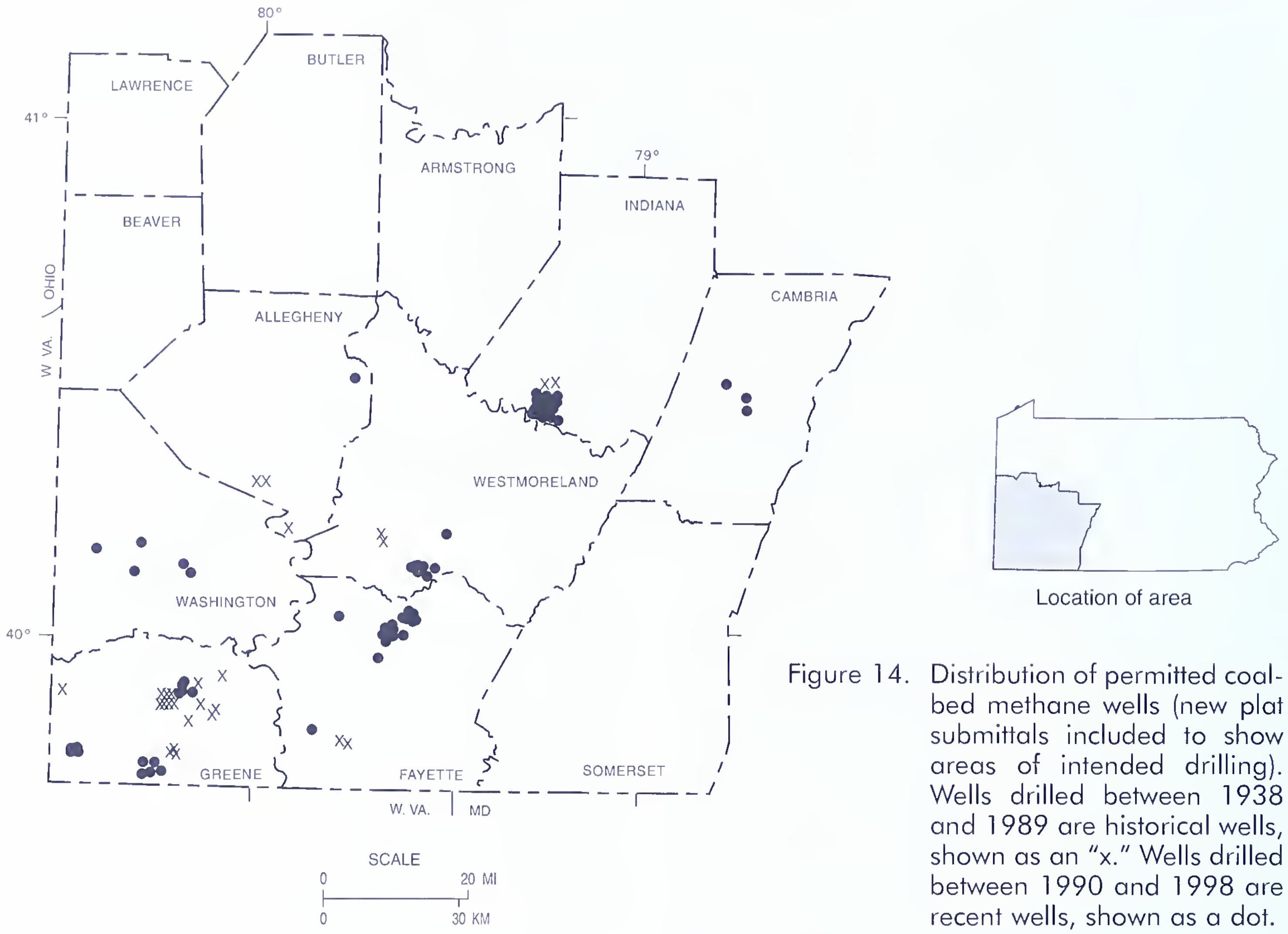

Figure 14. Distribution of permitted coal-bed methane wells (new plat submittals included to show areas of intended drilling). Wells drilled between 1938 and 1989 are historical wells, shown as an "x." Wells drilled between 1990 and 1998 are recent wells, shown as a dot.

sheet by Markowski (2000). Coal beds are discussed in descending stratigraphic order.

Fayette County

Smiley Pool, Highhouse Field (1938)

The earliest serendipitous discovery of significant gas flow from coal reported from routine well-record processing (at this writing) dates back to 1938 from the Smiley pool. The Smiley pool, in the Highhouse field, southwestern Fayette County, is about ¾ mile southeast of the Fayette anticlinal axis and about 1 mile northwest of the Uniontown synclinal axis in the Smithfield 7.5-minute quadrangle (Figure 13, pool 18), and between the 1,100- and 1,200-foot structure contours on the base of the Pittsburgh coal (Shaulis, 1985). Two Duquesne Natural Gas Company wells yielded open flows of 100 Mcf at 751 to 755 feet from an unidentified Allegheny Formation coal; in one well, the interval between 747 and 770 feet (including associated noncoal units) was perforated but not stimulated. The well record reports this interval as a "perforated joint set." Depths of conventional gas shows were recorded from 596 to 1,869 feet. Total depth reached the Chadakoin Formation at 2,707 feet. Both wells produced from the gas sands of the deeper reservoirs of the Conemaugh Group and from an Allegheny Formation coal. One well is plugged and abandoned; the other is nonproducing.

Adelaide Pool, Waltersburg Field (1992, 1998)

The Adelaide pool, in the Waltersburg field, north-central Fayette County, is about a quarter of a mile northwest of the Uniontown synclinal axis in the Connellsville and Dawson 7.5-minute quadrangles (Figure 13, pool 19), and approximately on the 800-foot structure contour on the base of the Pittsburgh coal (Shaulis, 1985). The Equitable Resources Exploration USX Corporation No. 2 was drilled to the Mauch Chunk Formation at 1,540 feet. Perforations and stimulations from 1,053 to 1,389 feet targeted the Allegheny Formation (including the Clarion and Brookville coals) and the upper part of the Pottsville Formation. Natural open flows were 8 Mcfd and 84 Mcfd after treatment. Conventional natural gas was also produced from the Allegheny and Pottsville Formations. The well is nonproducing.

More recently, Belden and Blake Corporation drilled about 12 CBM wells whose localities are in the Connellsville and Dawson 7.5-minute quadrangles.

Perforated and stimulated zones range from 679 feet in the Upper Bakerstown coal to 1,459 feet in the Brookville coal, including associated noncoal units. Total depths range from 1,315 to 1,653 feet in the Pottsville Formation. Open flows were not reported. The wells are producing.

Moyer Pool, Mayfield Field (1992–93)

The Moyer pool, in the Mayfield field, north-central Fayette County, is less than a tenth of a mile east of the Uniontown synclinal axis in the Connellsville 7.5-minute quadrangle (Figure 13, pool 21), and between the 900- and 1,100-foot structure contours on the base of the Pittsburgh coal (Shaulis, 1985). The BTI Energy, Inc., Harrington No. 1A well (now operated by David L. Elliott) was drilled to a total depth of 45 feet in the Conemaugh Group and had no reported production. Although originally intended for CBM, it was junked and plugged.

BTI Energy, Inc. (now LAHD Energy, Inc.), drilled two conversion/gob wells. Perforations, without stimulations, ranged in depth from 1,005 to 1,048 feet in the Pittsburgh seam, and total depths reached 1,150 and 1,289 feet in the Conemaugh Group. Each well produced a natural open flow of 5 Mcfd and after-treatment open flows of 60 to 70 Mcfd, but excess water production interfered with the effectiveness of the wells and the gas production (David T. Bajek, personal communication, 1997). The wells are nonproducing.

Unnamed Pool, Masontown Field (1997)

An unnamed pool in the Masontown field, southwestern Fayette County, is about 2 miles west of the Fayette anticlinal axis (Figure 13, pool 15) and about 2 miles southeast of the Lambert synclinal axis in the Masontown 7.5-minute quadrangle, between the 840- and 920-foot structure contours on the base of the Pittsburgh coal (Shaulis, 1985). LAHD Energy, Inc., drilled the Dicenzo Tract 1 No. 3 to a total depth of 178 feet in the Monongahela Group as a conversion/gob well. The deepest depth targeted for production was 118 feet in the Monongahela. After-treatment open flows are not available. The well is dry and will be plugged, according to the well record.

Unnamed Pool, Kenneth Field (1997)

An unnamed pool in the Kenneth field, northwestern Fayette County, is about 4 miles northwest of the Fayette anticlinal axis (Figure 13, pool 16) and less than a tenth of a mile southeast of the Lambert synclinal axis in the Fayette City 7.5-minute quadrangle, between the 700- and 800-foot structure contours on the base of the Pittsburgh coal (Shaulis, 1985). LAHD Energy, Inc., drilled the Angelo No. 1, a conversion/gob well, to a total depth of 290 feet in the Monongahela Group. The deepest depth targeted for production was 165 feet in the Monongahela. After-treatment open flows are not available. The well is dry and will be plugged, according to the well record.

Allegheny County

Detwiler Pool, Forward Field (1962)

The Detwiler pool, in the Forward field, at the southern tip of Allegheny County, is about 2.5 miles northwest of the Waynesburg synclinal axis in the Monongahela 7.5-minute quadrangle (Figure 13, pool 14), and approximately on the 840-foot structure contour on the base of the Pittsburgh coal (Dodge, 1985). The Detwiler No. 1, drilled by Stephen S. Spinner, had a natural open flow of 327 Mcf for 96 hours in the Freeport coals (undifferentiated, as reported on the well record) at 1,002 to 1,006 feet from an open hole completion. The well went dry, was later drilled to 2,377 feet in the Venango Group, and had shows of conventional natural gas from 1,624 to 1,893 feet in the Burgoon Sandstone and in a deeper sandstone from 2,305 to 2,347 feet.

Indiana County

Campbells Mill Pool, Blairsville Field (1972, 1992–99)

The most significant CBM pool in Pennsylvania is the Campbells Mill pool in south-central Indiana County (Figure 13, pool 24). It is in the Blairsville field and in the Blairsville, Bolivar, and Indiana 7.5-minute quadrangles. The main body of the pool is dissected by the Fayette anticlinal axis on the western side and the Latrobe synclinal axis on the east. The Campbells Mill pool is situated approximately between the 460- and 680-foot structure contours in the Blairsville quadrangle, between the 440- and 580-foot structure contours in the Bolivar quadrangle, and between the 580- and 740-foot structure contours in the Indiana quadrangle, all on the base of the Upper Freeport coal (Bragonier and Glover, 1996). The Campbells Mill pool has the largest number of known commercial CBM wells, approximately 53 at this writing; 50 were drilled by Belden and Blake Corporation (formerly O'Brien Methane Production, Inc., and Canton Oil and Gas Company). The following coals of the Conemaugh Group, Allegheny Formation, and Pottsville Formation were targeted: Mahoning, Upper Freeport, Middle Freeport, Lower Freeport, Upper Kittanning, Middle Kittanning, Lower Kittanning, Clarion, Brookville, and Mercer. According to the well records, perforations ranged from 319 to 1,169.5 feet; natural open flows from 5 to 15 Mcfd; after-treatment open flows from 40 to 125 Mcfd; producing-interval depths from 749 to 1,170 feet; and total depths from 975 feet in the Pottsville Formation to 1,410 feet in Mississippian-age rocks. Belden and Blake also has 12 new wells in north-central Fayette County. The early Belden and Blake wells produced pipeline-quality gas at an average after-treatment open flow of 40 Mcfd. Water production is generally 115 barrels/day/well.

The other operator in Indiana County, LAHD Energy, Inc. (formerly Lee E. Minter), permitted three wells. Productive intervals and total depths ranged from 475 to 575 feet in Upper Freeport gob. Natural open flows ranged from 120 to 140 Mcfd. The wells produced on a short-term basis. They are nonproducing and inactive.

Unnamed Pool, Indiana Field (1981)

An unnamed pool in the Indiana field, also in south-central Indiana County, is about a quarter of a mile northwest of the Latrobe synclinal axis in the Indiana 7.5-minute quadrangle (Figure 13, pool 25), and between the 540- and 620-foot structure contours on the base of the Upper Freeport coal (Bragonier and Glover, 1996). It contains three 1981 Helvetia Coal Company test/service wells. The initial intent was to conduct fracturing tests on Upper Freeport and adjacent strata at depths from 622 to 638 feet. According to two of the well records, the Upper Freeport was treated open hole with 75 percent nitrogen-generated foam, then horizontally notched with sand and water. Immediately after drilling, fracture tests were completed, and all three holes were cemented from top to bottom. Total depths ranged from 655 to 670 feet. The wells were dry, then plugged and abandoned.

Greene County

Rudolph Run Pool, Gump Field (1975–76)

The first and oldest true "coal-bed methane well" in Pennsylvania was drilled in the Rudolph Run pool in the Gump field, south-central Greene County. Although the well was designed for degasification, not for commercial production and sale, it was still considered a CBM well. The pool is about a quarter of a mile west of the Bellevernon anticlinal axis in the Oak Forest 7.5-minute quadrangle (Figure 13, pool 6), just below the 440-foot structure contour on the base of the Pittsburgh coal (Dodge and Glover, 1984). The three methane degasification wells in this pool, drilled by Carnegie Natural Gas Company, produced from the Pittsburgh coal seam of the Monongahela Group (Figure 7). In the first well, perforations and stimulations into the Pittsburgh occurred from 674 to 680 feet; the second well had no treatment; and the third well was stimulated from 755 to 760 feet, but without perforation. Productive intervals occurred between 680 and 965 feet, natural open flows ranged from 0.19 to 14.9 Mcfd, and total depths ranged from 828 to 1,250 feet in the Conemaugh Group. The wells are plugged and abandoned due to the cost of well maintenance.

Unnamed Pool, Jefferson Field (1976)

An unnamed pool in the Jefferson field, northeastern Greene County, is about half a mile southeast of the Bellevernon anticlinal axis in the Mather 7.5-minute quadrangle (Figure 13, pool 11), and between the 580- and 620-foot structure contours on the base of the Pittsburgh coal (Dodge and Glover, 1984). The USBM drilled the Morgan No. 1 to a total depth of 934 feet in the Upper Freeport horizon. The abandoned workings of the Pittsburgh and rider coals were encountered from 332 to 341 feet, but no gas was reported. After-treatment open flows were not available. The deepest target depth was also 934 feet in the Upper Freeport horizon, but there was no production. The well is reported as dry.

Blairtown Pool, Waynesburg Field (1976–79)

The Blairtown pool in the Waynesburg field, central to north-central Greene County, is about half a mile southeast of the Waynesburg synclinal axis in the Waynesburg 7.5-minute quadrangle (Figure 13, pool 8), and between the 300- and 480-foot structure contours on the base of the Pittsburgh coal (Dodge and Glover, 1984). The main coal beds in the quadrangle are the Waynesburg, Sewickley, and Pittsburgh coals (Figure 7). The Pittsburgh coal underlies the entire Waynesburg quadrangle (Roen, 1970). The main seam is about 68 inches thick and has a thick lower main bench accompanied by one or more thinner beds and partings. According to Roen (1970), the Pittsburgh seam has been mined in the eastern half of the quadrangle. The Sewickley coal, which has an average thickness of 41 inches, does not crop out here (Roen, 1970).

Of the 10 Greene County pools, the Blairtown pool contains the most CBM or degasification wells (18 well records were submitted). The well drilling was part of the Lykes/Emerald Mines Project initiated in 1974 (see also "Selected Previous Studies in Pennsylvania," p. 15; and Hunt and Steele, 1991). The pre-mining degasification wells targeted the Pittsburgh coal and associated noncoal units (Figure 7). Half of the wells were drilled open hole with nitrogen-water foam stimulation (40 feet below casing); the other half were perforated and stimulated with fluid and sand (including associated noncoal units). Natural open flows ranged from 0 to after-treatment open flows of 100 Mcfd, mainly from the Pittsburgh seam, and productive intervals ranged from 582 to 1,022 feet (vertical hole) to 1,595 feet (slant hole). Production was not reported for about half the wells. Total depths ranged from 616 feet in the Monongahela Group to 1,022 feet in the Conemaugh Group, and the maximum slant hole depth was 4,802 feet to the Pittsburgh coal, according to the well record. Half the wells are plugged and abandoned; the others are nonproducing but not plugged.

Traces of brackish water were found at the depth of the Pittsburgh seam. This may be attributed to high-pH conditions, which are caused by the presence of carbonates (Goodarzi and Van der Flier-Keller, 1991). Slightly brackish water indicates a coastal or paralic depositional environment. Other geologic factors controlling the influx of some elements into coals are the following: (1) hydrologic conditions; (2) original plant communities; (3) coal rank; (4) nature of the country rock; and (5) basin characteristics and tectonic setting.

Unnamed Pool, Waynesburg Field (1977)

An unnamed pool in the Waynesburg field, east-central Greene County, is about 1 mile southeast of the Bellevernon anticlinal axis in the Oak Forest 7.5-minute quadrangle (Figure 13, pool 7), and between the 540- and 580-foot structure contours on the base of the Pittsburgh coal (Dodge and Glover, 1984). Famous for a 1983 Supreme Court case, Hoge versus U.S. Steel Corporation, the Mary Jo Hoge, et al. No. 1 was drilled by William L. Bentley, Jr. (who transferred ownership to Mary L. Cunningham) to a total depth of 1,420 feet with the initial intent of economically extracting methane gas. According to Geomega, Inc. (1977), key drilling targets were the Pittsburgh seam at a depth of 580 feet and the Upper Freeport at a depth of 1,220 feet. More than 9 feet of Pittsburgh coal was found, five other coal beds thicker than 3 feet were found, and the Upper Freeport was too thin for economic extraction (Geomega, Inc., 1977). Despite its thickness, low gas pressure in the Pittsburgh hindered production; there was the probability that the coal bed was draining off gas instead of contributing to production. Two conventional gas zones, however, were perforated and stimulated for production. The deepest target interval was reported at 1,249 feet in a Freeport sandstone and total depth at 1,420 feet in the Pottsville Formation. The well is reported as dry. (See the section "The Coal-Bed Methane Ownership Quandary," p. 64, for a discussion of the Hoge versus U.S. Steel Corporation case.)

Unnamed Pool, Waynesburg Field (1978)

A second unnamed pool in the Waynesburg field, east-central Greene County, is about 1 mile southeast of the Bellevernon anticlinal axis (Figure 13, pool 12), and near the 600-foot structure contour on the base of the Pittsburgh coal in the Waynesburg 7.5-minute quadrangle (Dodge and Glover, 1984). Sidewall cores were collected for desorption analysis for the Kinloch Development Corporation Stoner No. 1, but no additional information was obtained. Open-hole production of conventional gas from the Allegheny and Pottsville Formations yielded a natural open flow of 29 Mcfd and 10 Mcfd after treatment. The deepest producing depth was 1,290 feet (associated noncoal units from 1,260 to 1,290 feet were stimulated) in the Pottsville Formation, and total depth reached 1,333 feet in the Salt sand. The well is classified as dry.

Frosty Run Pool, Waynesburg Field (1978)

The Frosty Run pool, in the Waynesburg field, east-central Greene County, is about 3 miles southeast of the Bellevernon anticlinal axis (Figure 13, pool 13) and about 1.6 miles northwest of the Whiteley synclinal axis in the Garards Fort 7.5-minute quadrangle, between the 500- and 520-foot structure contours on the base of the Pittsburgh coal (Dodge and Glover, 1984). Two Kinloch Development Corporation exploratory wells were drilled to test the coals of the Monongahela Group and Allegheny Formation (and associated gas sands) for gas potential. The Murdoch No. 1–1 had a show of gas and 80 barrels/day of water, and sidewall cores were collected for desorption analysis. The well was also logged and fractured for CBM production. The Clarion and Brookville coal interval, including associated noncoal units, was perforated and stimulated from 1,344.5 to 1,490.75 feet; total depth reached 1,607 feet in the Pottsville Formation. The well was pumped intermittently for several weeks, and gas flow was reported, but gas/water production was not measured (Adams and others, 1984). After an eight-stage Kiel treatment was begun, open flow was 15 Mcfd; high injection pressure required stages 2 and 3 to be shortened, and the treatment ended after stage 3; the well flowed back for several days, then was cleaned out. Post-stimulation injection tests revealed that of four zones stimulated, three were positively affected (Adams and others, 1984). The well is nonproducing.

The Murdoch No. 2–1 is dry. Total depth reached 862 feet in the Pittsburgh seam.

Turner Pool, Waynesburg Field (1980, 1987, 1997)

The Turner pool, in the Waynesburg field, north-central Greene County, is about 2 miles northwest of the Bellevernon anticlinal axis and about 2 miles southeast of the Waynesburg synclinal axis in the Waynesburg 7.5-minute quadrangle (Figure 13, pool 9), and between the 420- and 480-foot structure contours on the base of the Pittsburgh coal (Dodge and Glover, 1984). Five wells were drilled in the Turner pool. Two were drilled by Waynesburg College, the Thayer Hall Tract No. 1 and Thayer Hall Tract No. 2 wells. According to the well record, the 1,450-foot-deep (to the Pottsville Formation) Waynesburg College production well, Thayer Hall Tract No. 1, penetrated the following coal seams (most of the coal thicknesses below are rounded off for convenience): the Waynesburg from 152 to 158 feet; the Sewickley from 374 to 378 feet; the Pittsburgh rider from 480 to 489 feet (TRW Energy Systems Group, 1980) as stated on the well record; the Pittsburgh from 490 to 497 feet; the Bakerstown from 894 to 897 feet; the Upper Freeport from 1,090.5 to 1,091.2 feet; the Upper Kittanning from 1,193 to 1,194 feet; the Middle Kittanning from 1,241 to 1,243 feet; the Clarion from 1,298 to 1,301 feet; and the Mercer from 1,407 to 1,409 feet. The Pittsburgh, Bakerstown, Upper Kittanning, Middle Kittanning, Clarion, and Mercer coals were stimulated from 496.8 to 1,416.2 feet. The Waynesburg College well had a natural open flow of 5 Mcfd and an after-treatment open flow of 20 Mcfd. Dewatering yielded between 120 and 230 barrels/day of water and a maximum gas flow of 30 Mcfd (Adams and others, 1984). Gas contents ranged from 70 cf/t for the Waynesburg coal to 195 cf/t for the Upper Kittanning coal. The Mercer was not tested; however, it was estimated to contain 141 cf/t (Adams and others, 1984). According to Byrer and others (1984), final gas production was 22 Mcfd accompanied by less than 2 barrels/day of water. Thayer Hall Tract No. 1 produced for eight to nine years at 20 to 30 Mcfd, and the gas was used to heat campus buildings. Charles W. Byrer (personal communication, 1991) also stated that the well produced for about nine years, but stopped producing in 1989. According to Barbara Duffield (personal communication, 1991), the well became inoperable due to mechanical problems. Thayer Hall Tract No. 2 was dry, then plugged and abandoned; total depth reached 610 feet in the Conemaugh Group.

The third well in the Turner pool, Turner No. 2, produced little CBM and conventional gas from the Monongahela Group through the Allegheny Formation at 10 Mcfd after nitrogen foam frac treatment (Charles Headlee, personal communication, 1998). No well record is available to determine perforated intervals. The well is shut in and inactive, according to the operator. The fourth well, Turner No. 3, also produced small amounts of both types of gas from the perforated intervals (668 to 1,589 feet) of the Sewickley, Pittsburgh, and Mahoning coals and associated noncoal units. It produced 50 Mcfd after treatment, which later trickled down to 10 Mcfd, accompanied by high water production. The deepest producing depth was at 1,589 feet in the Allegheny Formation, and the total depth reached 1,902 feet in the Pottsville Formation. The well is shut in and inactive (Del Johnson, personal communication, 1998).

More recently, Jesmar Energy, Inc., drilled the fifth well (gob well) in the Turner pool, Cyprus Southern Realty Corporation No. 1. It was completed open hole to a total depth of 571 feet in an open mine (Pittsburgh coal gob). Gas shows were reported at 531 feet and the natural open flow was 450 Mcfd. The gas quality was low in Btu. The well is producing.

Poverty Run Pool, Pratt Storage Field (1983)

The Poverty Run pool, in the Pratt storage field, north-central Greene County, is 1 mile northwest of the Bellevernon anticlinal axis and about 3 miles southeast of the Waynesburg synclinal axis in the Waynesburg 7.5-minute quadrangle (Figure 13, pool 10), and between the 580- and 620-foot structure contours on the base of the Pittsburgh coal (Dodge and Glover, 1984). Henderson Mining Company (Emway Resources, Inc.) drilled the Phillips/Rush No. 1 as a degasification well; no production was reported. The well was to be monitored for an unspecified length of time before stimulation in the Allegheny Formation. The deepest target depth and total depth was 1,035 feet in the Upper Freeport coal. The well is nonproducing.

Dunkard Fork Pool, Rich Hill Field (1983)

The Dunkard Fork pool, in the Rich Hill field, northwestern Greene County, is about 1.25 miles northwest of the Washington anticlinal axis in the Wind Ridge 7.5-minute quadrangle (Figure 13, pool 1), and between the 560- and 580-foot structure contours on the base of the Pittsburgh coal (Dodge and Glover, 1984). Waynesburg Energy Group drilled the Scherich No. 1, which produced 1.1 Mcfd natural open flow. The deepest producing target depth was 347 feet in the Pittsburgh seam. Total depth reached 392 feet in the Conemaugh Group. The well is plugged and abandoned.

Windy Gap Pool, New Freeport Field (1991)

The Windy Gap pool, in the New Freeport field, southwestern Greene County, is about half a mile southeast of the Nineveh synclinal axis in the New Freeport 7.5-minute quadrangle (Figure 13, pool 5), and between the 120- and 220-foot structure contours on the base of the Pittsburgh coal (Dodge and Glover, 1984). CNG Producing Company drilled five CBM wells in the New Freeport field. Perforated intervals, ranging from 633 to 1,756 feet, targeted the Waynesburg "A," Waynesburg, Sewickley, Pittsburgh, Lower Freeport, and Upper Kittanning coals and associated noncoal units (Figure 7). Total depths ranged from 1,330 to 2,130 feet. Productive intervals ranged from 1,140 to 1,756 feet. Natural open flows were too small to test, but after hydraulic fracture stimulation, the open flows were estimated to be 50 Mcf. The gas was relatively free of contaminants and yielded a Btu value acceptable for pipeline-quality control. Traces of fresh water were found at some of the shallower coal depths in three of the five wells. CNG reported brackish water near a deep coal in one of the wells. The wells are plugged and abandoned due to the economics of well maintenance.

Westmoreland County

Waltz Mill Pool, Oakford Field (1978–79)

The Waltz Mill pool, in the Oakford field, southwestern Westmoreland County, is about 2 miles southwest of the Grapeville (Jacksonville) anticlinal axis in the Smithton 7.5-minute quadrangle (Figure 13, pool 17), and between the 750- and 820-foot structure contours on the base of the Upper Freeport coal (Skema, 1988). Two Westinghouse Electric Corporation wells penetrated Pennsylvanian rocks exclusively, one as an observation well, the other as a methane gas well. The Fee Land No. 4 produced from the Lower Freeport, Upper Kittanning, Lower Kittanning, Clarion, Mercer, and Sharon coals (Figure 7). Perforations and stimulations occurred at the 193- to 658-foot zone (including associated noncoal units). According to Adams and others (1984), in April 1978 the well produced gas at 38 Mcfd along with 240 barrels/day of water. By late May, gas flow remained constant, and water flow decreased to approximately 120 barrels/day. During January 1980 the Fee Land No. 4 produced 856 Mcf, having an average production of 28 Mcfd to a maximum of 43 Mcfd. The deepest productive depth occurred at 658 feet in the Pottsville Formation. Total depth was 750 feet in the Pottsville Formation.

In the observation well, Fee Land No. 5, a total of 27 feet of coal contained between 187 feet in the Upper Freeport and 629 feet in the Sharon was penetrated. Gas contents ranged from 13 to 102 cf/t and had a weighted average of 37 cf/t (Adams and others, 1984). Desorption values indicated an average content of 186 cf/t, yielding a computed coal-bed resource estimate of 1.85 MMcf/acre following Kiel hydraulic stimulation (Westinghouse Electric Corporation, 1979). The noncoal interval, 549 to 551 feet, was perforated. Total depth was 741 feet in the Pottsville Formation.

Additional core-sample analyses suggested that the in-place resource is 8 MMcf/acre, higher than originally estimated. These wells were part of a project initiated by Westinghouse Electric Corporation to test for a supply of gas for space heating in a nearby facility. Both wells are now nonproducing.

Morewood Pool, Mayfield Field (1992–93)

The Morewood pool, in the Mayfield field, south-central Westmoreland County, is about 1 mile northwest of the Uniontown (Latrobe) synclinal axis in the Mount Pleasant 7.5-minute quadrangle (Figure 13, pool 20), and between the 960- and 1,020-foot structure contours on the base of the Pittsburgh coal (Skema, 1988). Equitable Resources Exploration drilled the USX Corporation No. 3 well and perforated and stimulated into the Conemaugh Group, the Allegheny and Pottsville Formation coals, and associated noncoal units (Figure 7). Productive intervals ranged from 683 to 1,096 feet (including the Lower Kittanning and Clarion coals). The natural open flow was too small to test, but after treatment, open flow was 146 Mcfd. Total depth was 1,168 feet in the Pottsville Formation. The well is plugged and abandoned.

The USX Corporation No. 2 penetrated Allegheny and Pottsville coals (Figure 7). Productive intervals ranged from 848 to 1,086 feet (including the Upper Kittanning, Lower Kittanning, Clarion, and Mercer coals). After treatment, open flow was 40 Mcfd. There was no natural open flow. Total depth was 1,215 feet in the Pottsville Formation. The well is plugged and abandoned.

Orchard Hill Pool, Hoggs Field (1994)

The Orchard Hill pool, in the Hoggs field, south-central Westmoreland County, is about a third of a mile southeast of the Uniontown (Latrobe) synclinal axis in the Mount Pleasant 7.5-minute quadrangle (Figure 13, pool 22), and between the 980- and 1,080-foot structure contours on the base of the Pittsburgh coal (Skema, 1988). Equitable Resources Exploration drilled one well that perforated the Brush Creek, Upper Freeport, Upper Kittanning, Clarion, and Mercer coals, and associated noncoal units (Figure 7). These intervals ranged from 688 to 1,116 feet. The operator was unable to gage the natural open flow, but after-treatment open flow was 10 Mcfd. Total depth was 1,269 feet in the Pottsville Formation. The well is plugged and abandoned.

Ramsay Terrace Pool, Armbrust Field (1997)

The Ramsay Terrace pool, in the Armbrust field, south-central Westmoreland County, is about a tenth of a mile east of the Uniontown (Latrobe) synclinal axis in the Mount Pleasant 7.5-minute quadrangle (Figure 13, pool 23), and between the 840- and 880-foot structure contours on the base of the Pittsburgh coal (Skema, 1988). The Dicenzo Tract 1 No. 4, a LAHD Energy, Inc., conversion well, targeted the Pittsburgh gob in an open mine. The deepest target depth and total depth reached 270 feet in the Pittsburgh gob. Zero open flow was reported and after-treatment flows were not available. The well is dry (David L. Elliott, personal communication, 1999).

Washington County

Unnamed Pool, Mehaffy Field (1989)

An unnamed pool in the Mehaffy field, western Washington County (Figure 13, pool 2), is about a tenth of a mile southeast of the Claysville anticlinal axis in the West Middletown 7.5-minute quadrangle, and between the 720- and 740-foot structure contours on the base of the Pittsburgh coal (Skema, 1987). The Allegheny Pittsburgh Coal Company drilled the Zappi Tract No. 1 and targeted the Pittsburgh coal, but the gas yield was too small to measure. No further treatment followed. The deepest target depth and total depth were at 1,025 feet in the Pottsville Formation. The well is dry, and plugged and abandoned.

South Franklin Pool, Lagonda Field (1991)

The South Franklin pool, in the Lagonda field, central Washington County, is about half a mile northwest of the Washington anticlinal axis in the Washington West 7.5-minute quadrangle (Figure 13, pool 4), and between the 660- and 680-foot structure contours on the base of the Pittsburgh coal (Skema, 1987). Jesmar Energy, Inc., reported a natural open flow of 3,000 Mcfd from the Pittsburgh (Figure 7) gob zone in the Varner No. 1, completed as an open-hole well. The gas was treated by enrichment with propane, nitrogen, and carbon dioxide (Mark V. Leidecker, personal communication, 1997). The productive interval ranged from 485 to 490 feet. Total depth reached 504 feet in the Pittsburgh gob zone. The well is producing and on line.

Jesmar Energy, Inc., also cooperated with United Energy Development Consultants, Inc., Energy Systems Associates, and Consolidated Natural Gas to "fully evaluate the technical and economic feasibility of the use of low Btu (sub-pipeline-quality) gas as an oxidizer and medium to low Btu mine drainage gas as a primary fuel source in gas turbines" (U.S. Department of Energy, 1995, p. 2). This will be a precursor to testing mine-ventilation air for gas turbine uses. End uses for electrical generation would be for powering mine-site equipment or for local utility use.

Unnamed Pool, Washington-Taylorstown Field (1994)

An unnamed pool in the Washington-Taylorstown field, central Washington County (Figure 13, pool 3), is about a tenth of a mile west of the Finney synclinal axis in the Washington West 7.5-minute quadrangle, and between the 700- and 760-foot structure contours on the base of the Pittsburgh coal (Skema, 1987). The Jesmar Energy, Inc., Foster No. 1 well was drilled into an open mine through Pittsburgh gob from 362 to 367 feet (367 feet was also the total depth). The well did not yield any gas and is plugged and abandoned.

Cambria County

Unnamed Pool, Munster Field (1990–98)

An unnamed pool in the Munster field, south-central Cambria County, is about half a mile west of the Wilmore synclinal axis in the Ebensburg 7.5-minute quadrangle (Figure 13, pool 27), and between the 900- and 1,100-foot structure contours on the base of the Lower Kittanning coal (Glover, 1990). LAHD Energy, Inc., completed nine conversion wells in an abandoned mine (11 permit numbers are known). Two of the 11 wells are on line (David L. Elliott, personal communication, 2000). Natural open flows were reported as not available on the well records. Target zones were the Upper Freeport, Lower Freeport, Middle Kittanning, and Lower Kittanning seams. Perforated intervals ranged from 440 to 550 feet deep in three of the wells. Gob gas production was from the Lower Freeport, Middle Kittanning, and Lower Kittanning coals; the gas only needed to be dried (water vapor is removed from the gas stream during processing prior to compression for the pipeline), and the quality was close to 1,000 Btu (David L. Elliott, personal communication, 2000). The total depths ranged from 547 to 1,052 feet.

Powell Pool, Carrolltown Field (1993)

The Powell pool, in the Carrolltown field, central Cambria County, is about ¾ mile southeast of the Laurel Hill anticlinal axis in the Colver 7.5-minute quadrangle (Figure 13, pool 26), and between the 2,000- and 2,050-foot structure contours on the base of the Lower Freeport coal (Glover, 1990). CNG Producing Company completed the Bilonick No. 1 in an abandoned mine. The well reached a total depth in the Upper

Freeport seam (Figure 7) at 254 feet (also the deepest producing depth). A natural open flow yielded 84 Mcfd. The gas was 48 percent methane, and there was sporadic production. The well is nonproducing, inactive, and will be plugged; it was also not close enough to the pipeline (Arnold B. Fairman, personal communication, 1997).

METHODS

SAMPLING

The method for determining the gas content and composition of coal samples was patterned after the direct method of testing, which was used by the USBM (Close and Erwin, 1989; Diamond and Levine, 1981) from 1972 until its closure in 1996 and subsequently by NIOSH. The direct method has previously been used successfully in France and consists basically of bleeding gas off a canister of coal into a water-filled inverted graduated cylinder until atmospheric pressure is attained in the canister. The displacement of water represents the amount of gas desorbed at the time of measurement. Results from the direct method can be used for resource evaluation and recoverability of the methane or for ventilation specifications by multiplying the total coal tonnage estimated for a given area by the methane content per ton of coal.

Coal samples for this project were obtained from exploratory core holes after permission was obtained from private coal companies. The entire coal bed, including carbonaceous shale partings, was tested for methane gas content and composition. Chemical analyses were also performed for some of the coals. Some of the coals were divided into subsamples for ease of handling and to ensure sample integrity.

TEST EQUIPMENT

Sample canisters of various diameters for different sized cores were constructed and modified to fit individual coal core samples. These standard containers were made from PVC plumbing pipe that can hold up to 50 pounds of internal pressure. Standard valve assemblies having a quick-connect capability for the release of gas were built into the top cap. The top cap was then fitted and sealed to the pipe section.

To measure emission, the desorbed gas is conducted through a flexible tube attached securely to the valve head of the container and into a water-filled, inverted graduated cylinder that is in a 2-inch-deep pan filled with water (the cylinder should be about ¾ to 1 inch above the base of the pan) (Figure 15). Gas flows into the cylinder until atmospheric pressure is reached in the container. The water level is read before and after the gas is released. The volume of water

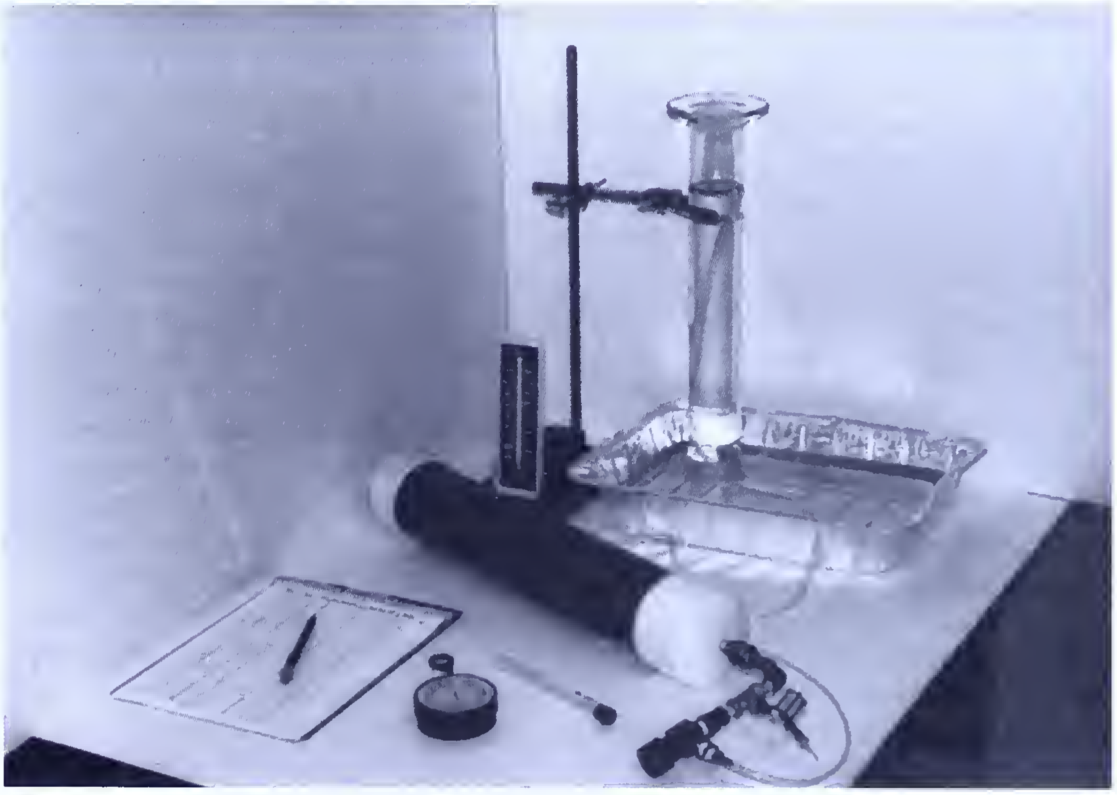

Figure 15. Equipment used by the Pennsylvania Geological Survey for the direct method of measuring the volume of desorbed gas (as explained in Diamond and Levine, 1981).

displaced is equal to the volume of gas emitted. The valve is then closed until the next reading. The date, time, volume of gas released (in cubic centimeters), and the emission rate (cc/day) are recorded. This test is performed at the drill site and at regular intervals in the laboratory. This desorption process is continued until a very low emission rate (about 10 cc/g/day [320 cf/t] for 1 week) is obtained (Diamond and Levine, 1981).

DETERMINING TOTAL GAS CONTENT

After the core is retrieved from the borehole, the core sample is placed as soon as possible in an airtight container and measured for desorbed gas. The gas lost from the coal while it was being cored is estimated by a graphical method, which is described below. The gas content-in-place of a coal bed is determined by adding the values for gas lost during coring (L) and the gas measured during desorption (D) divided by the sample weight (SW), plus the residual gas in the coal (R). The calculation for the total gas content is thus [(L+D)/SW] + R (Diamond and Levine, 1981). In this study, desorbed and cumulative desorbed gas values only were corrected to STP (standard temperature and pressure).

Lost Gas

The gas that escapes from the coal from the time it is released from the confining pressures of the drill hole until it is sealed in the sample container is called "lost gas." Since this component of total gas content cannot be directly measured, its determination requires the application of mathematical models. The amount of lost gas depends on the drilling medium, drilling technique, and the time required to place the core into the container. This time is the lost-gas time in minutes from the beginning of gas desorption to sample containment (Diamond, Irani, and others, 1986). If air or mist is used as the circulating/lubricating medium for drilling, it is assumed that the coal begins giving off gas immediately upon penetration of the core barrel. If water or mud is used, desorption is assumed to begin when the core is halfway out of the hole, that is, when the gas pressure is assumed to exceed that of the hydrostatic head. Thus, the lost-gas time in minutes can be determined based on the type of circulating medium used. If air or mist is used, the lost-gas time is equal to the time the core is sealed in the container (A) minus the time the coal bed is encountered (B). If water is used, the lost-gas time is equal to the time the core is sealed in the container (A) minus the time it reaches the surface (C), added to the time the core reaches the surface (C) minus the time it starts out of the hole (D) divided by 2. Therefore, lost-gas time equals (A−C) + [(C−D)/2].

Readings of desorbed gas from the sealed sample are taken frequently for the first few hours of emission. Providing that environmental conditions are relatively stable (the ideal temperature is 70°F), the volume of gas given off is proportional to the square root of the desorption time for those first few hours. A plot of the total emission after each reading against the square root of the desorption time generally produces a straight line (Figure 16). Even before a sample is placed in a container, it has already been desorbing gas for several minutes (the lost-gas time). Therefore, the line must originate at the point on the x-axis that equals the square root of the lost-gas time. In the example shown in Figure 16 for the lower part of the Sewickley coal bed, the lost-gas time is 24 minutes, and the square root of that value is 4.9. The succeeding values of x are calculated as the square root of the lost-gas time plus the elapsed time for each reading. The point where the constructed line intercepts the negative y-axis is the estimated amount of lost gas (Diamond and Levine, 1981; McCulloch, Levine, and others, 1975). For this part of the Sewickley, the lost-gas value is 95 cc (5.8 in.^{3}).

After about 10 hours, the emissions are too irregular to extrapolate. Under less than ideal conditions, the lost-gas calculation must be estimated if a straight line cannot be produced. Also, coals that vary in physical character and density can influence the rate and amount of gas emitted.

Desorbed Gas

The total volume of gas emitted from the sample and measured by the direct method is the desorbed gas. The frequency of testing depends on the inherent gassiness of the coal. Initial readings at the drill site should be taken at short intervals, sometimes every 10 minutes for a very gassy coal (approximately greater than 1,000 cc [61 in.^{3}]); otherwise, readings should be taken once every hour for three or more hours. In general, the emission rate then becomes low enough to require only one reading per day for a few days. The sample is then monitored every third or fourth day for about 2 to 3 weeks. Afterward, it is monitored on a weekly or bimonthly basis, depending on how gassy the sample is. For example, when the desorption rate falls below 0.05 cc/g (1.6 cf/t) for 5 consecutive days or less than 50 cc (3.1 in.^{3}) per week, the readings are

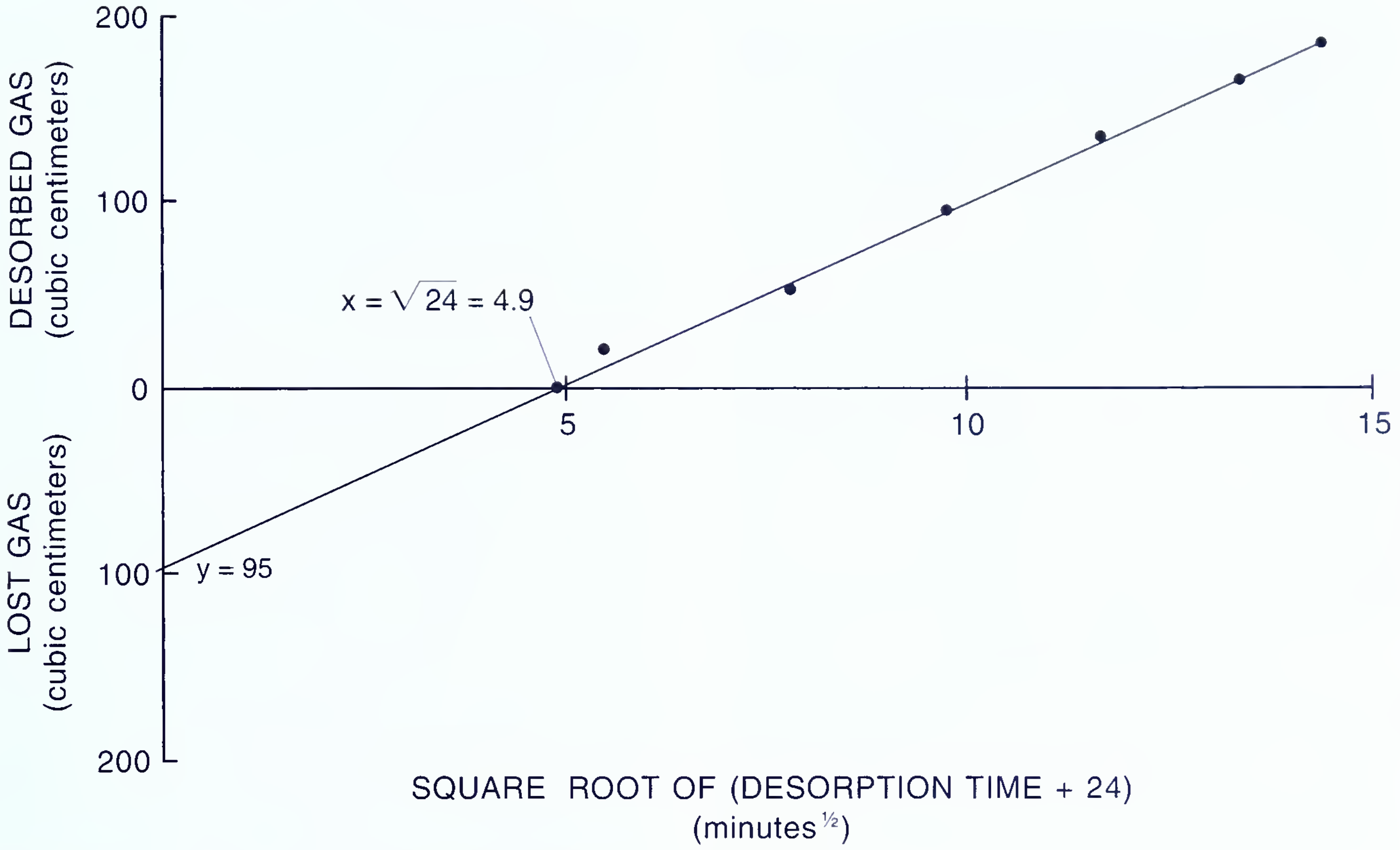

Figure 16. Example of the graphical method used to determine the amount of lost gas for a coal sample, in this case, the lower part of the Sewickley coal bed in Greene County.

discontinued (McCulloch, Levine, and others, 1975). Because temperature affects the emission rate, the sample should be kept at a fairly constant temperature (approximately 70°F) during the desorption period.

Residual Gas

The amount of residual gas remaining in the coal depends on the physical nature of the coal, that is, the friability or blockiness of the coal. Friable coals release their gas more quickly. "Friable coals emit nearly 96 percent of the total gas during desorption whereas a blocky coal emits only 60 percent of its total gas" (McCulloch, Levine, and others, 1975, p. 1).

Even when the daily desorption rate is less than 0.05 cc/g (1.6 cf/t), the coal still contains residual gas. The amount of residual gas is determined by the fracture network that defines coal friability. What makes coals friable is not completely known. According to McCulloch, Levine, and others (1975), some factors may be the following: depth of the coal bed beneath the surface, coal rank, cleat spacing, amount of fixed carbon, Hardgrove grindability index, and the degree of tectonic disturbance. Blocky coals, such as the Pittsburgh coal, have fewer fractures and a cleat spacing of about 1 inch (McCulloch, Levine, and others, 1975); thus, they tend to release their gas more slowly.

To estimate the residual gas in the coal cores, 200-gram samples were crushed to about −200 mesh inside a large ball mill. The gas released by this method is the gas that was trapped in the matrix of the coal. To determine the amount of residual gas, the gas measured in cubic centimeters is divided by the weight of the crushed sample in grams. According to Close and Erwin (1989), determination of residual gas is not always necessary, since this component is trapped in the reservoir microporosity during well depressurization and in most cases is an insignificant volume. The counterpoint, however, is that "for low diffusion rate coals in which lost gas is low, the residual gas component may be relatively large" (McLennan and others, 1995, p. 42).

SAMPLES

This study also involved a compilation of two data sets from 455 samples (Appendices 1 through 5; Figures 2 and 6). The first data set includes new gas-content determinations, composition, and coal chemistry from six drill holes in central Armstrong County, central Cambria County, north-central Greene County, and north-central Somerset County (Figure 2 and Table 1; Figure 6). Thirty core samples from 10 coal beds were tested. In addition, supplemental data were provided by industry for north-central Fayette County, south-central Greene County, and northern Westmoreland County (Figure 2; Table 1); 32 samples from 10 coal beds were tested. The second data set is a compilation of previously published USBM, USDOE, and MRCP data from 393 samples, plus the data obtained by the Pennsylvania Geological Survey. The 393 samples were obtained from 40 bituminous and anthracite coal beds in central and southern Allegheny County, south-central Armstrong County, most of Greene County (except for the eastern part), southern and central Indiana County, central Lackawanna County, western and central Schuylkill County, and throughout Washington and Westmoreland Counties (Figure 2; Table 1). Both data sets were compiled for graphical analysis (Appendices 3 through 5). Because of the general lack of correlation between gas content and atmospheric pressure or temperature, graphs showing these relationships are not included in this report.

NEW FIELD-SAMPLE LOCATIONS AND TEST RESULTS

ARMSTRONG COUNTY

The Upper and Lower Kittanning coal beds were tested for their methane content from two drill holes in Kittanning Township, Whitesburg 7.5-minute quadrangle (Figure 2 and Table 1; Figure 6). These coals are high-volatile bituminous coals. The sites were 0.38 to 0.47 miles east of the Greendale-Sprankle Mills anticlinal axis, and the distance to previous mining was 0.3 mile (Glover, in preparation). At drill hole A1, the depth to the base of the Upper Kittanning was 275 feet, and it was 419 feet for the Lower Kittanning (Appendices 1 and 3). Respective depths at drill hole A2 were 132 and 257 feet (Appendices 1 and 3). Total gas contents ranged from 9 to 26 cf/t (Appendices 1 and 3). Gas contents were not expected to be high due to the shallow depths and relative proximity to previous mining. The average methane composition of the Upper Kittanning coal was 73 percent; it was 89 percent for the Lower Kittanning coal (Appendix 2).

Graphs in Appendix 3 reveal a direct association between total gas content and depth of coal. The deeper coals also happen to be thicker at this site, so there appears to be a correlation between greater thickness and an increase in total gas content. There was no apparent correlation between total gas content and atmospheric pressure or temperature. However, the amount of cumulative gas appeared to increase slightly in direct proportion to atmospheric pressure and temperature. There was a steady increase in cumulative gas with elapsed time. After about 100 days, the amount of cumulative gas stabilized. The above samples were limited to about 100 days of testing due to company needs; the samples discussed below were not limited in length of time for testing.

CAMBRIA COUNTY

The Upper and Lower Freeport seams were encountered at 724 and 771 feet, respectively, in drill hole B1 in Cambria Township, Ebensburg 7.5-minute quadrangle (Appendices 1 and 3; Figure 2 and Table 1; Figure 6). These coals are medium-volatile bituminous in rank. The site was about 1 mile west of the Wilmore synclinal axis and 3.4 miles east of the Ebensburg anticlinal axis (Glover, 1990). The site was also about 1 mile from a mine dump and 4.5 miles west-northwest of a strip mine. Total gas contents ranged from 156 cf/t for the Upper Freeport to 298 cf/t for the Lower Freeport (Appendices 1 and 3). The Upper Freeport was the thicker of the two seams at 5.27 feet compared to the Lower Freeport at 2.77 feet (Appendices 1 and 3). The gas composition of the Upper Freeport seam was 99 percent methane; it was 96 percent methane for the Lower Freeport seam (Appendix 2).

Graphs in Appendix 3 illustrate a direct relationship between total gas content and depth of coal. There was no correlation between thickness of the coal and total gas content. There also was no apparent correlation between total gas content and atmospheric pressure or temperature. It was noted that cumulative gas appeared to increase slightly with an increase in atmospheric pressure and temperature. The amount of cumulative gas increased steadily with elapsed time but stabilized after 150 to 200 days.

GREENE COUNTY

Five coal beds were sampled from two drill holes, one in Wayne Township, Oak Forest 7.5-minute quadrangle, the other in Washington Township, Waynesburg 7.5-minute quadrangle (Appendices 1 and 3; Figure 2 and Table 1; Figure 6). These coals are high-volatile A bituminous in rank. The D1 site was 0.66 mile west of the Bellevernon anticlinal axis. Figures 5 and 13 show the location of this axis. The coal beds encountered ranged from the Waynesburg “A” at 510 feet to the Pittsburgh at 934 feet (Appendices 1 and 3). Total gas contents ranged from 51 cf/t for the Waynesburg "A" to 216 cf/t for the Sewickley coal (Appendices 1 and 3). The other site, D2, was 1.25 miles west-southwest of the Pittsburgh deep mined-out areas (Figure 2; Table 1). Structurally, it is 0.83 mile east of the Amity anticlinal axis and 1.4 miles west of the Waynesburg synclinal axis (Dodge and Glover, 1984), which is shown in Figures 5 and 13. The coal beds encountered ranged from the thin Ten Mile coal at 351 feet to the Sewickley coal at 938 feet (Appendices 1 and 3). Total gas contents ranged from 30 cf/t for the Ten Mile coal to 98 cf/t for the Sewickley coal (Appendices 1 and 3). For the Sewickley, thickness correlated with an increase in gas content. The gas composition varied from an average of 85 percent methane for the Waynesburg "A" and Sewickley coals to 93 percent for the Little Washington coal (Appendix 2).

Graphs in Appendix 3 reveal the importance of depth and thickness to increased total gas content. There was no apparent correlation between total gas content and atmospheric pressure or temperature. Correlations between cumulative gas and temperature or atmospheric pressure were vague but slightly positive. The amount of cumulative gas increased proportionally with elapsed time and reached a plateau at about 250 to 300 days.

SOMERSET COUNTY

The Middle and Lower Kittanning seams were sampled from two drill holes in Stonycreek Township, Stoystown 7.5-minute quadrangle (Figure 2 and Table 1; Figure 6). These coals are low-volatile bituminous in rank. Drill holes E1 and E2 were in a strip mine about 500 feet from old mine workings; they were also about half a mile east of the Negro Mountain anticlinal axis (shown in Figure 5) (Berg and Dodge, 1981). Due to their proximity to an active mine site and the shallowness of the seams, allowing gas to escape, these coals revealed very low gas contents. The Middle Kittanning averaged about 28.5 cf/t and the Lower Kittanning about 25.5 cf/t (Appendices 1 and 3). Despite the thickness of the Middle and Lower Kittanning coals, about 6 and 10 feet, respectively, their shallow depths (75 to 145 feet) were not conducive to the production of large amounts of methane (Appendices 1 and 3). The gas composition averaged less than 1 percent methane (Appendix 2). These values were anomalously low because the escape of methane and/or the mixing of air can occur at shallow depths, in fractures, or near active mine sites.

Graphs in Appendix 3 do not show a correlation between total gas content and depth or thickness of the coal in this case. There also was no apparent correlation between total gas content and atmospheric pressure or temperature. There was a weak correlation between the amount of cumulative gas and atmospheric pressure and temperature. Until about 220 days, the amount of cumulative gas increased at a steady rate.

OTHER DATA

An additional 32 samples were obtained from a series of drill holes and ventilation boreholes in Fayette, Greene, and Westmoreland Counties (Figure 2; Table 1).

In the Dunbar-Perry area of Fayette County, in the Dawson 7.5-minute quadrangle, a series of 14 drill holes, C1 to C14, was tested for total methane gas content. The drill holes were on the flanks of the Fayette anticlinal axis (Shaulis, 1985; Figure 13). Coal seams penetrated were the Lower Kittanning, Clarion, and Brookville. Depths to the base of the high-volatile bituminous coal beds ranged from 333 feet for the Lower Kittanning to 1,270 feet for the Brookville (Appendices 1 and 3). Gas contents ranged from 10.9 to 286.0 cf/t (Appendices 1 and 3). The graphs in Appendix 3 indicate that direct correlations exist between gas content and depth. Thickness plays a role also, but is not as obvious an indicator in these data.

A Greene County gob gas ventilation borehole in Wayne Township, Oak Forest 7.5-minute quadrangle, was located in the unnamed pool of the Gump field west of the Bellevernon anticlinal axis (Figures 5 and 13). The borehole penetrated six high-volatile bituminous seams, from the Waynesburg "A" at 510 feet to the Pittsburgh at 934 feet (Appendices 1 and 3). The Sewickley at 840 feet had the highest total gas content (Appendices 1 and 3). The methane composition of the mine gob gas ranged from 58 to 96 percent (Appendix 2).

A series of nine drill holes, F1 to F9, was tested for gas in Derry Township, Westmoreland County, in the Blairsville and Saltsburg 7.5-minute quadrangles (Figure 2; Table 1). The drill holes were on the eastern flank of the Greensburg synclinal axis (Skema, 1988). The target seam was the Upper Freeport, which ranged in depth from 598 to 720 feet (Appendices 1 and 3). The graphs in Appendix 3 show a general correlation between depth and higher gas contents. The thicker coals in this case also appeared to have higher gas values.

It is difficult to nearly impossible to evaluate the methane drainage potential in the Anthracite region. Due to the economics of drilling in a region of complex structure and stratigraphy, few projects were initiated here. In Lackawanna and Schuylkill Counties, about 30 samples from nine coal beds were tested for their gas contents (Diamond, LaScola, and Hyman, 1986) (Figure 2; Table 1; refer to Figure 8 for coal-seam nomenclature). The results were quite different from the results for the Main Bituminous field. The Big Bed in Lackawanna County yielded 54 cf/t at the minimum basal depth of 102 feet. The Mammoth seam of Schuylkill County had only 13 cf/t at the deepest basal depth of 1,719 feet. Also in Schuylkill County, the Orchard seam, at 1,359 feet, yielded the lowest gas content at 6.4 cf/t, and the 685-foot Peach Mountain seam in Schuylkill County produced the highest at 691 cf/t. The Peach Mountain seam had the highest gas content, but porosity and permeability were very low (Trevits and others, 1986). Another drill hole indicated a high gas content in the Tunnel coal at 482 cf/t. Even with stimulation and bottom hole pumps, the presence of water in the hole and the low permeability of the anthracite inhibited further flow of gas for production. Due to complex folding and deformation in the region, certain areas have anomalously high gas rates at shallow depths and low gas rates at deeper depths. The CBM potential here is thought to be questionable because of the low permeability and high cost of exploration and production in a complex geologic setting. However, a 675 cf/t gas content determination by Kim (1977) and new adsorption results from RMB Earth Science Consultants Ltd. (1998) may stimulate further investigation in this area.

DISCUSSION OF ALL TEST RESULTS

GENERAL TRENDS

A total of 455 samples compiled from the MRCP, USDOE, USBM, the Pennsylvania Geological Survey, and new supporting data discussed above provided the basis for a variety of graphs plotted to examine relationships and trends (Appendices 4 and 5). Graphs in Appendix 4 represent different ranks of bituminous and anthracite coal and illustrate the relationship between depth to the base of the coal bed and total gas content. The largest group, the 358 high-volatile A bituminous coal samples, shows a general rise in gas content with depth; gas contents range from 3 to 298 cf/t and depths from 47 to 1,294 feet. The seven low-volatile bituminous coal samples show a rise in gas content with depth; gas contents range from 24 to 298 cf/t and depths from 75 to 1,060 feet. The 30 anthracite samples display anomalously low gas contents at depths greater than 1,200 feet; gas contents range from 6 to 688 cf/t and depths range from 102 to 1,719 feet. As mentioned previously, the anomalous values are thought to occur because of folding and deformation in the region. The sparse data that does exist for the Anthracite region implies that anthracite coal has high methane volumes, but because of low porosities and permeabilities, it does not normally have good production rates with or without artificial stimulation.

Appendix 4 also contains graphs based on different ranks of bituminous coal and anthracite coal illustrating the relationship of thickness of the coal bed versus total gas content. Low-volatile coals exhibit a negative correlation between gas content (24 to 298 cf/t) and thickness (2.77 to 10.40 feet). The 25 anthracite samples that had reported thicknesses show anomalously low and high gas contents (6 to 586 cf/t) and thicknesses less than 2 feet. Most ranks show no discernable correlation between thickness and gas content; their thicknesses range from 0.47 to 6 feet and gas contents range from 13 to 230 cf/t.

The 455 samples represented in the graphs of Appendix 5 show the relationship of depth to the base of the coal bed versus total gas content based on roof lithology (as noted from the USBM and the Pennsylvania Geological Survey) and rank to determine the effectiveness of the overlying strata on gas entrapment. For high-volatile A bituminous samples having a shale roof, there is a rise in gas content with depth. The medium- and low-volatile bituminous coals lack gas content-depth relationships. Results from various roof lithologies for anthracite lack discernable patterns.

A total of 418 samples represented in the graphs of Appendix 5 shows the relationship of thickness versus total gas content based on roof lithology. The high-volatile A bituminous group displays no relationship between thickness and gas content. The medium- and low-volatile bituminous samples do not show any thickness-gas content relationships. The 23 anthracite samples do not reveal any correlation between thickness and gas content.

The relationship between thickness and gas content remains inconclusive for this study. The data suggest that there is no correlation between the two parameters. However, in general, most of the data in this report suggest a direct correlation between depth of the coal bed and total gas content.

GAS CONTENTS

Based on aggregate data available from Pennsylvania Geological Survey exploration drilling, from results directly from industry, and from the USBM (Diamond, LaScola, and Hyman, 1986), 24 coals (21 bituminous and 3 anthracite) have relatively large gas contents, greater than or equal to 125 cf/t (Table 4).

Table 4. *Depth and Rank of Coal Seams Having Gas Contents Greater Than or Equal to 125 cf/t*

County	Coal bed	Total gas content (/t)	Depth to base of coal bed (feet)	Rank
Allegheny	Upper Freeport	134	488	Not available
do.	do.	157	491	High-volatile A
do.	do.	157	492	do.
do.	do.	150	493	do.
do.	Middle Kittanning	160	801	Not available
Cambria	Upper Freeport	156	724	Low-volatile
do.	Lower Freeport	298	771	do.
Fayette	Lower Kittanning	140	417	High-volatile A
do.	do.	174	618	do.
do.	do.	171	791	do.
do.	do.	208	801	do.
do.	do.	234	845	do.
do.	do.	258	856	do.
do.	do.	281	996	do.
do.	Clarion	286	878	do.
do.	do.	206	1,090	do.
do.	Brookville	215	547	do.
do.	do.	257	695	do.
do.	do.	172	1,270	do.
Greene	Washington	125	486	do.
do.	Waynesburg "B"	128	501	do.
do.	Waynesburg	144	974	do.
do.	Upper Waynesburg	131	558	do.
do.	do.	134	615	do.
do.	do.	160	696	do.
do.	Lower Waynesburg	138	560	High-volatile B
do.	do.	141	699	High-volatile A
do.	do.	160	700	do.
do.	Sewickley	216	840	do.
do.	do.	154	372	do.
do.	do.	128	495	do.
do.	do.	157	589	do.
do.	do.	173	590	do.
do.	do.	173	592	do.
do.	do.	182	643	do.
do.	do.	128	645	do.
do.	do.	166	646	do.
do.	do.	163	772	do.
do.	do.	157	773	do.
do.	do.	141	856	do.
do.	do.	138	857	do.
do.	do.	134	859	do.
do.	do.	138	1,181	do.
do.	Redstone	191	888	do.
do.	Pittsburgh rider	138	913	do.
do.	do.	134	485	do.
do.	do.	125	743	do.
do.	do.	173	748	do.
do.	do.	154	827	do.
do.	Pittsburgh	147	488	do.
do.	do.	134	490	do.
do.	do.	182	492	do.
do.	do.	224	581	do.
do.	do.	230	582	do.
do.	do.	221	590	do.
do.	do.	234	593	do.

Table 4. *(Continued)*

County	Coal bed	Total gas content (cf/t)	Depth to base of coal bed (feet)	Rank
Greene	Pittsburgh	198	610	High-volatile A
do.	do.	240	612	do.
do.	do.	230	622	do.
do.	do.	224	624	do.
do.	do.	224	626	do.
do.	do.	179	666	do.
do.	do.	128	675	Not available
do.	do.	150	678	High-volatile A
do.	do.	208	680	Not available
do.	do.	230	681	High-volatile A
do.	do.	166	682	do.
do.	do.	237	701	do.
do.	do.	250	703	do.
do.	do.	266	705	do.
do.	do.	246	716	do.
do.	do.	176	720	do.
do.	do.	147	749	do.
do.	do.	211	750	do.
do.	do.	205	752	do.
do.	do.	202	753	do.
do.	do.	202	755	do.
do.	do.	192	762	do.
do.	do.	138	762	do.
do.	do.	170	762	do.
do.	do.	170	778	Not available
do.	do.	179	786	High-volatile A
do.	do.	182	836	do.
do.	do.	205	837	do.
do.	do.	202	839	do.
do.	do.	131	857	do.
do.	do.	192	859	do.
do.	do.	182	905	do.
do.	do.	195	906	do.
do.	do.	157	953	do.
do.	do.	186	955	do.
do.	do.	138	957	do.
do.	do.	128	960	do.
do.	do.	179	961	do.
do.	do.	176	1,184	do.
do.	do.	218	1,272	do.
do.	do.	192	1,276	do.
do.	do.	221	1,280	do.
do.	Bakerstown	141	890	do.
do.	Freeport	157	1,415	Not available
do.	do.	179	1,417	do.
do.	Upper Freeport	150	937	do.
do.	do.	150	1,036	do.
do.	do.	230	1,058	do.
do.	do.	150	1,304	do.
do.	do.	144	1,307	do.
do.	Upper Kittanning	160	1,188	High-volatile A
do.	do.	211	1,189	do.
do.	Clarion	141	1,294	do.
Indiana	Lower Freeport	230	398	Medium-volatile
do.	Middle Kittanning?	339	656	do.
do.	Lower Kittanning	368	575	do.

Table 4. *(Continued)*

County	Coal bed	Total gas content (cf/t)	Depth to base of coal bed (feet)	Rank
Indiana	Lower Kittanning	246	576	Medium-volatile
do.	do.	125	579	do.
do.	do.	246	576	do.
do.	do.	246	579	do.
do.	do.	442	759	do.
Schuylkill	Tunnel	448	604	Anthracite
do.	do.	403	606	do.
do.	do.	586	608	do.
do.	Peach Mountain	602	685	do.
do.	do.	691	685	do.
do.	Seven Foot leader	397	817	do.
do.	do.	397	817	do.
Washington	Uniontown	144	340	High-volatile A
do.	do.	125	465	do.
do.	Sewickley	154	660	do.
do.	Pittsburgh rider	157	464	do.
do.	do.	138	518	do.
do.	do.	147	624	do.
do.	do.	173	625	do.
do.	do.	154	655	do.
do.	do.	147	657	do.
do.	do.	157	672	do.
do.	do.	141	726	do.
do.	do.	157	760	do.
do.	do.	134	761	do.
do.	do.	189	791	do.
do.	Pittsburgh	160	520	do.
do.	do.	138	521	do.
do.	do.	138	523	do.
do.	do.	125	524	do.
do.	do.	131	556	do.
do.	do.	150	627	do.
do.	do.	160	628	do.
do.	do.	179	630	do.
do.	do.	170	631	do.
do.	do.	189	647	do.
do.	do.	128	660	do.
do.	do.	179	661	do.
do.	do.	163	663	do.
do.	do.	150	665	do.
do.	do.	131	676	do.
do.	do.	141	677	do.
do.	do.	182	717	do.
do.	do.	154	718	do.
do.	do.	160	720	do.
do.	do.	138	729	do.
do.	do.	141	731	do.
do.	do.	128	732	do.
do.	do.	176	793	do.
do.	do.	166	798	do.
Westmoreland	Harlem	150	372	do.
do.	Upper Bakerstown	125	440	do.
do.	Brush Creek	182	627	do.
do.	Mahoning	253	674	Medium-volatile
do.	Upper Freeport	146	627	High-volatile A
do.	do.	175	708	do.

Table 4. *(Continued)*

County	Coal bed	Total gas content (cf/t)	Depth to base of coal bed (feet)	Rank
Westmoreland	Upper Freeport	170	716	High-volatile A
do.	do.	164	639	do.
do.	do.	177	646	do.
do.	do.	221	720	do.
do.	do.	275	607	do.
do.	do.	298	728	do.
do.	Upper Kittanning	179	570	do.
do.	do.	250	780	do.
do.	do.	246	786	Medium-volatile
do.	do.	278	806	do.
do.	Middle Kittanning	189	637	High-volatile A
do.	do.	176	637	do.
do.	do.	202	641	do.
do.	do.	157	790	do.
do.	do.	269	790	do.
do.	do.	227	866	Medium-volatile
do.	Lower Kittanning	358	1,060	Low-volatile
do.	Clarion?	134	955	High-volatile A
do.	do.	163	966	do.
do.	Clarion	198	691	do.
do.	do.	166	691	do.
do.	do.	256	835	do.
do.	do.	272	835	do.
do.	do.	240	835	do.
do.	Brookville	240	994	Medium-volatile
do.	Mercer	182	1,042	do.

The bituminous coals, in descending order, are the Washington, Waynesburg "B," Upper Waynesburg, Lower Waynesburg, Uniontown, Sewickley, Redstone, Pittsburgh rider, Pittsburgh, Harlem, Upper Bakerstown, Brush Creek, Mahoning, Upper Freeport, Lower Freeport, Upper Kittanning, Middle Kittanning, Lower Kittanning, Clarion, Brookville, and Mercer; the anthracite coals, in descending order, are the Tunnel, Peach Mountain, and Seven Foot leader. Depths range from 340 feet in the Uniontown coal of Washington County to 1,417 feet in the Freeport coal (name as reported) of Greene County. The highest gas contents, greater than or equal to 300 cf/t (Table 5), were in five coals (two bituminous and three anthracite) as follows: Mid-

Table 5. *Depth and Rank of Coal Seams Having Gas Contents Greater Than or Equal to 300 cf/t*

County	Coal bed	Total gas content (cf/t)	Depth to base of coal bed (feet)	Rank
Indiana	Middle Kittanning?	339	656	Medium-volatile
do.	Lower Kittanning	368	575	do.
do.	do.	442	759	do.
Schuylkill	Tunnel	448	604	Anthracite
do.	do.	403	606	do.
do.	do.	586	608	do.
do.	Peach Mountain	602	685	do.
do.	do.	691	685	do.
do.	Seven Foot leader	397	817	do.
do.	do.	397	817	do.
Westmoreland	Lower Kittanning	358	1,060	Low-volatile

dle Kittanning(?), Lower Kittanning, Tunnel, Peach Mountain, and Seven Foot leader at depths ranging from 575 feet in the Lower Kittanning of Indiana County to 1,060 feet in the Lower Kittanning of Westmoreland County.

GAS COMPOSITION AND BTU VALUES

The 30 coal cores (representing 10 coal beds) retrieved from six industrial exploratory drill holes were monitored for their gas composition from as little as one month to as long as 11 months. The other 32 samples were provided by industry. Analyses of gas composition (Appendix 2) reveal that the coals sampled whose depths are more than 300 feet (Table 4) generally have about 90 percent or greater methane content. Samples having low methane values indicate a shallow coal and/or a loss of methane and the introduction of nitrogen to the coal with time. For example, in general, methane contents will be lower if active mining of the target seam is taking place nearby.

Higher molecular-weight hydrocarbons such as ethane, propane, pentane, and butane were present and are common constituents in CBM. After several months, these constituents began to increase as the methane decreased.

Because the gas samples were tested in 20-cc (1.22 in.^{3}) glass vacutainers capped with rubber stoppers, extremely sensitive laboratory methods detected traces of the unsaturates 1-butene, ethylene, and propylene, not normally found in CBM at ambient temperature. High amounts of nitrogen may be due to air mixing with the sample upon testing over a long period of time and/or simply the decomposition of nitric organic compounds. Traces of nitrogen are formed during coalification. Traces of carbon dioxide are also a product of oxidation as well as coalification. Traces of carbon monoxide, not normally found in CBM, are probably a product of oxidation over time.

Pennsylvania Geological Survey samples tested for gas chemistry include the following: A1–1 through A2–2b, B1–1a through B1–2b, D2–1 through D2–5b, and E1–1a through E2–2b (Appendix 2, Table 6; Appendix 3, Table 7). The Somerset County samples, E1–1a through E2–2b, have been excluded from the median calculation because of their extremely shallow depth and proximity to active mining (Appendices 1 and 3). Approximate median values of various components of coal-bed gas from these samples are the following: 94 percent methane, 4.1 percent carbon dioxide, 0.7 percent nitrogen, 0.3 percent ethane, 0.01 percent carbon monoxide, 0.002 percent n-butane, 0.001 percent propane, and 0.0002 percent isobutane.

Heating values of the coals (reported on a dry, ash-free basis) increase from about 14,700 Btu/lb in Beaver and Lawrence Counties to a maximum of nearly 15,800 Btu/lb in northern Somerset and southern Cambria Counties and in the Broad Top and Georges Creek areas (Socolow and others, 1980) (Figure 3). Heating values decline eastward in the Anthracite region to about 14,400 Btu/lb in Carbon County (Socolow and others, 1980) (Figure 3).

Heating values from coal samples in this study averaged 15,209 Btu (daf) (Appendix 1). Heating values from gas samples in this study averaged about 1,000 Btu/scf, comparable to conventional natural gas values (Appendix 2). The samples having lower methane contents also had very low heating values and generally lower gas contents (Figures 17 and 18). High methane values, on the other hand, do not always guarantee high gas contents.

ESTIMATES OF GAS-IN-PLACE

MINE EMISSIONS

According to Bibler and others (1997), methane emissions from coal mining account for about 10 percent of the annual global methane emissions from anthropogenic sources. The United States is the third largest emitter of coal-mine methane after the People's Republic of China and the former Soviet Union (primarily Russia and Ukraine). Although 40 percent of United States coal is produced in underground mines, these mines generate more than 70 percent of estimated methane emissions from coal mining.

According to Trevits and others (1991), 294.9 MMcfd of methane was vented to the atmosphere from 487 deep mines in the United States in 1988. Approximately 150,000 homes could be heated per year with an estimated 50 percent effective recovery of these emissions. In 1988, West Virginia, Alabama, Virginia, and Pennsylvania produced more than 35 MMcfd of methane emissions. Generally, in southwestern Pennsylvania, mine-emission data are from the Pittsburgh seam, and sometimes they are used in an empirical relationship that uses emission data to approximate trends in gas-in-place data (gas-in-place equals 20 percent of gas emission and coal production). These values do not always agree with values from the USBM direct method used in this report.

As of 1998, there were 91 active deep mines in Pennsylvania, of which 53 occurred in bituminous mines; 15 of these were reported as gaseous (Pennsylvania Department of Environmental Protection, 1998). In the Anthracite region, there were 38 active deep mines, of which eight were reported as gaseous. Most of the bituminous mines are in the study area. According to Joseph A. Sbaffoni (personal communication,

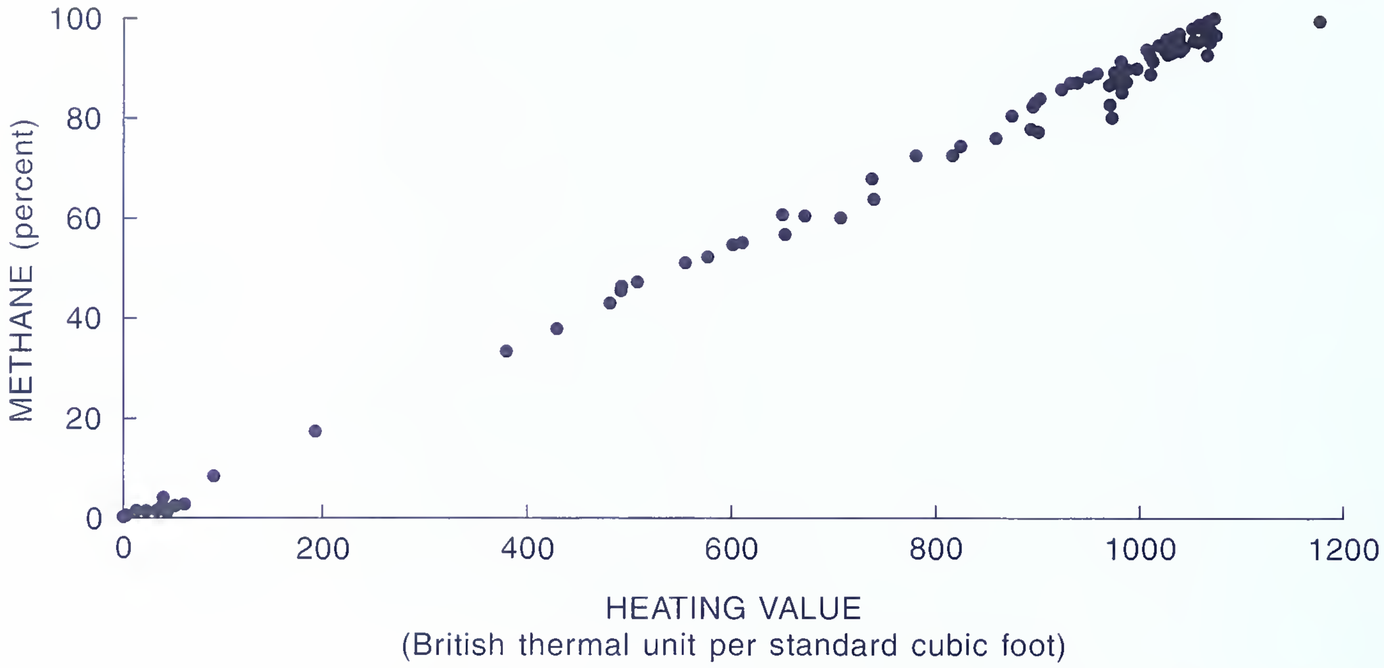

Figure 17. Heating values based on percent methane for coal seams in Armstrong, Cambria, Greene, and Somerset Counties.

2001), detected methane amounts as low as 25/100 of a percent in underground coal mines are considered gassy. The U.S. Mine Safety and Health Administration records coal-mine methane readings that show concentrations greater than 50 parts per million; in 1999, all mines emitting at least 0.1 MMcfd were reported (U.S. Environmental Protection Agency, 2001). The most recent figures for Pennsylvania (Pennsylvania Department of Environmental Protection, 1999) revealed 79 active deep mines, 53 occurring in bituminous mines. The number of gaseous mines was not reported. According to the U.S. Environmental Protection Agency (2001), total coal-mining emissions in 1999 for Pennsylvania were 27,003 MMcf (this includes emissions from underground mines, surface mines, and post-mining activities). In general, the higher the gas content of the coal beds, the higher the mine emissions; however, the gas content data from deep coal beds do not account for the decrease in permeability, which causes a decrease in methane emissions (Grau and LaScola, 1984). At greater depths (more than 2,000 feet), the increase in gas content is small due to low permeabilities associated with deeper coal beds (coal fractures compress with depth of burial) (Berger Associates, 1978).

Since the early 1990s, there have been significant developments in the recovery of coal-mine methane in the United States, mainly in the number of active recovery-and-use projects. The number of mines having active recovery-and-use projects has grown from 10 in 1994 to 17 in 1997, accounting for an estimated recoverable amount of from 35 Bcf in 1994 to almost 49 Bcf in 1996 (Bibler and others, 1997). This growth was stimulated by four main factors, as follows: (1) more coal-mine operators are familiar with methane-recovery technology; (2) the expansion of coal-mine methane uses beyond pipeline injection; (3) further legislation on ownership issues in most CBM producing states; and (4) profit-generating potential tested and proven by various coal-mine methane recovery projects.

As of 1998, according to the web site of the Coalbed Methane Outreach Program (U.S. Environmental Protection Agency, 2000), approximately 43 Bcfy of coal-mine methane was recovered for use, instead of being wastefully vented to the atmosphere (the recovery is equivalent to removing an estimated 3.8 million cars from the road). According to Bibler and others (1997), 79 profiled mines in 11 states liberated an estimated 382 MMcfd of methane (140 Bcfy) in 1996. The total estimated emissions in 1996 were 248.4 MMcfd (45.7 Bcfy); of these, 35 percent of the estimated methane liberated is used. With the implementation of recovery projects, an estimated 18.3 to 27.4 Bcfy of coal-mine methane could be reduced, assuming a 40 to 60 percent recovery efficiency (equivalent to about 8 to 12 MMty [million tons per year] of carbon dioxide) (Bibler and others, 1997).

The three states having the largest number of profiled mines were West Virginia (14), Illinois (13), and Pennsylvania (12). The 12 active deep mines profiled in Pennsylvania liberated and emitted (because the methane was not used, these values are the same) an estimated 55.1 MMcfd (19.7 Bcfy) of coal-mine meth-

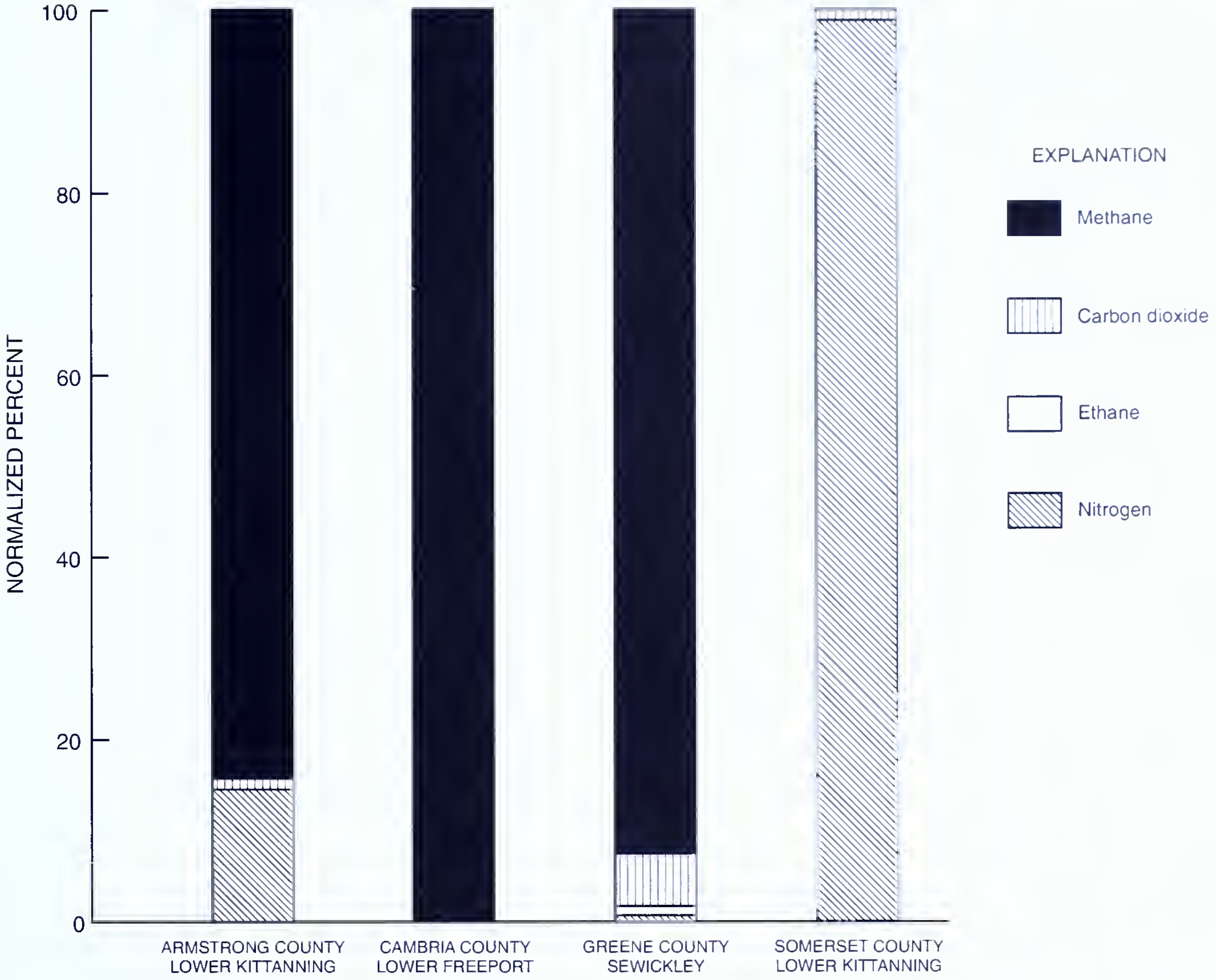

Figure 18. Gas composition for selected coal beds in Armstrong, Cambria, Greene, and Somerset Counties.

ane in 1996 (Table 2); if recovery projects are implemented, an estimated 7.9 to 11.8 Bcfy of methane emissions could be reduced (Bibler and others, 1997). Estimated coal-mine methane ventilation emissions, drainage, liberation, specific emissions, Btu values of recovered methane, drainage systems and efficiency, and coal seam, production, and quality data for the 12 mines are presented in Table 2.

COMPARATIVE RESOURCE AND RESERVE ESTIMATES

The target area for commercial development in the Northern Appalachian coal basin, and in Pennsylvania in particular, is described by an irregular ellipse (Figure 1). This is where the deepest coal beds occur compared to other parts of the state. The 27 CBM pools of Pennsylvania are also located in this target area (Figure 13). Overall estimates of CBM resources indicate that there may be 61 Tcf of gas contained in the coal of the basin (Kelafant and others, 1988). The estimated resource of CBM for southwestern Pennsylvania and northwestern West Virginia is 51 Tcf of gas-in-place (Kelafant and others, 1988). This resource could potentially heat 70 million homes for a year, assuming 50 percent effective recovery.

In Pennsylvania, the most complete information relates to the blocky, high-volatile Pittsburgh coal bed. In Greene County, the virgin Pittsburgh coal is estimated to contain a total reserve of 375 Bcf of natural gas (Kim, 1975). Kim (1974, 1975) reported more than 500 Bcf for Greene and Washington Counties combined. To be conservative, a 60 percent recovery rate was applied. These estimates become, respectively, 225 and 300 Bcf (Briggs and Tatlock, 1999); total estimates for these counties in the Monongahela Group are, respectively, 260 and 344 Bcf (Geomega, Inc., 1983). According to Geomega, Inc. (1983, p. 32), a "conservative estimate of natural gas recoverable from coalbeds totals 2,654 Bcf, of which well over half is classified probable and possible." This number includes the estimates for the Anthracite fields and the Main Bituminous field of southwestern Pennsylvania. (Pottsville Formation and Conemaugh Group coals were omitted because of their sporadic occurrence; also excluded were bituminous coal beds within 2 miles of outcrops or mines to ensure at least 500 feet of cover. In the Anthracite fields, areas less than 1 mile from the outcrop of the Llewellyn Formation were excluded due to the steeply dipping strata, and coals more than 5 feet thick in the lower part of the formation were included to reflect depths greater than 1,000 feet and areas not mined.) According to Geomega, Inc., the "probable" classification is based on the presence of a total coal thickness of 6 feet or more in a probable coal zone; the "possible" classification is based on the presence of a possible coal zone totaling 6 feet or more in thickness; and a single coal bed less than 6 feet thick is classified as "speculative." Because the gas estimates from the Anthracite region are based on so few data, the anthracite part of the total resource estimate is speculative (Geomega, Inc., 1983). However, additional investigation in this region may prove worthwhile because of the 675 cf/t gas content (Kim, 1977) and new, promising adsorption results from RMB Earth Science Consultants Ltd. (1998).

THE COAL-BED METHANE OWNERSHIP QUANDARY

The technology exists to develop CBM in Pennsylvania, but questions still arise as to the ownership of gas or mineral rights of a coal bed(s). In the 1983 Pennsylvania Supreme Court case U.S. Steel Corporation versus Hoge, claims to ownership of CBM were tenuously given to the coal owner or lessee of a severed coal title by "ownership-in-place." After review of the severance deed, it was noted that the parties did not intend to limit the CBM rights and thus quieted (made secure by freeing from dispute or question) entitlement to U.S. Steel Corporation, the coal owner. This case did not set a precedent or resolve the issue, however, because claims have been made on behalf of the oil and gas owner or lessee, the surface owner, the coal owner, and any combination of the above. It is not automatic to assume in Pennsylvania that a coal owner is the sole owner of CBM. The language of the individual deed will be the determinant in resolving the issue of intent to CBM ownership, especially CBM that has migrated into noncoal strata.

In the United States, coal owners claim that, because the gas is contained in the coal matrix (coal serves as both the reservoir rock and source of gas), and because the coal owner asserts control over the coal, the gas belongs to the coal owner or lessee (Counts, 1990). Oil and gas owners claim that they have the right to produce gas from any strata, including coal beds, if present. They define CBM as a gas, and are not concerned about its source or reservoir. A third claim is that the ownership of CBM belongs to the owner of the mineral rights exclusive of oil, gas, and coal. The "extraneous" mineral estate is vested with the surface owner.

The federal government attempted to address this issue on May 12, 1981, when the U.S. Department of the Interior issued an opinion concerning ownership of CBM. The Department claimed that a "reservation of 'coal' to the United States does not include coal-bed methane" (Counts, 1990, p. 66). The claim also stated that the gas "does include gas found in coal deposits and, therefore, is disposable as a gas under Section 17 of the Mineral Leasing Act" (Counts, 1990, p. 66).

In Pennsylvania and the rest of the Northern Appalachian coal basin, unresolved ownership questions coupled with multiple land situations have hindered the commercial development of CBM. Because of this, it is important for the estate owner to negotiate a "multiple-use agreement" that will let each owner or lessee develop a plan or deed while allowing for the possibility of competing estates. Development in this area has been slow, but an increasing number of enterprising companies are now exploring, testing, and producing from the target area for commercial use. Lewin and others (1993) examined the pros and cons of six possible judicial solutions and one legislative solution (forced pooling) as listed here: (1) CBM belongs to the gas owner; (2) CBM belongs to the coal owner; (3) priority of severance; (4) case-by-case basis title search and analysis; (5) successive ownership: the coal owner owns the coal and the gas-in-place, but the gas lessee owns the migratory gas; (6) mutual simultaneous rights: gas owners have title to CBM, but coal owners have the right to extract CBM and gob gas simultaneously with mining as an incidental mining right; and (7) any successful development will depend on compromises between the oil and gas developer, the landowner, and the coal company. Federal legislation is working to effect a cooperative "forced (involuntary) pooling" of methane ownership, modeled after the Virginia Gas and Oil Act of 1990. Here, the landowners, coal owners, and gas owners would share the title or rights to the methane through escrow provisions that encourage development amidst pending disputes. This seeks to "protect the rights of coal owners to ensure coal-bed methane development is consistent with mine safety and production of the value of the coal resource" (Koen, 1991, p. 22). Thus, coal owners can still object to CBM development that would affect their coal reserves.

Section 1339 of the National Energy Policy Act of 1992, H.R. 776, contains CBM provisions patterned after the 1990 Virginia law. These provisions are effective in states where uncertainty over ownership is impeding CBM development unless these states adopt their own regulatory statutes or elect to exclude themselves from coverage.

A resolution was sought from the legislature asking the Department of Interior to delete Pennsylvania as an affected state after a series of meetings between the boards representing the coal industry and the oil and gas industry. Pennsylvania is no longer an affected state (Carl Morgeneier, personal communication, 1995). Board members concluded that current oil and gas statutes are sufficient to address CBM issues. No agreement was reached between the coal and oil and gas industries on the ownership issues.

There is still no ideal method that satisfies all participants, just ways to circumvent the ownership problem. Each situation will have to be dealt with on a case-by-case basis. The language of the individual deed will help determine the issue of intent to CBM ownership. The forced pooling mechanism does not address extraction-related conflicts that exist when noncoal owners have a right to develop CBM. Its success depends on the feasibility of regulating these conflicts. The best way, Lewin and others (1993) contended, may be a system of compulsory negotiation that results in binding arbitration.

ECONOMIC INCENTIVES

As with other nonconventional fuels, CBM was once eligible for a tax-incentive credit (at this writing, however, the tax credit does not exist). This provision, established by Section 29 of the Crude Oil Windfall Profit Tax Act of 1980, was crucial to the economic feasibility of many CBM recovery projects for which the drilling was completed before the end of 1992. This tax credit rewarded producers faced with high initial costs in developing nonconventional energy sources in the year of production. Wells or facilities that qualified had to be drilled after December 31, 1979, and to be in service by January 1, 1993 (Soot, 1991); January 1, 2003, is the extension date for production credit (Appalachian Basin Report, 1990). CBM formerly qualified for a special tax credit for nonconventional fuel sources worth about $0.85 to $0.90 per MMBtu (million British thermal units) as determined by the inflation adjustment factor and reference price for the particular calendar year (U.S. Internal Revenue Service, 1991).

Section 29 tax credits are not needed to make CBM wells economic, but they encourage accelerated exploration and development. Tax credits would, however, especially benefit the development of gob gas wells and the cost of collecting and processing the gas, which is usually low or marginal in Btu value. Lewin (1995) suggested that the best alternative to the tax credit would be a program that funded a subsidy for methane recovery using a methane emission fee. "The negative attributes of emission fees and subsidies would tend to neutralize each other, thereby avoiding any net cost to taxpayers, minimizing the impact on the price of coal, and minimizing the distortion of resource allocation between underground and surface coal or between coal and other fuels" (Lewin, 1995, p. 11). Lewin also recommended that tax credits be given for utilization once again, or flaring of the gas, because the environmental gains from flaring are just as important as using the gas for energy.

According to the U.S. Environmental Protection Agency (2001), Senate Bill S. 596, "Energy Security and Tax Incentive Policy Act of 2001," was recently proposed. This bill would provide for a resurgence of new tax incentives to encourage the production and efficient use of energy resources. It provides for a tax credit of $1.21 per Mcf (1 million Btu) for the capture and use of coal-mine methane as a fuel source. Coal-mine methane is defined in the bill as "any methane gas which is being liberated, or would be liberated during qualified coal mining operations or as a result of past qualified coal mining operations, or which is extracted up to 10 years in advance of mining" (U.S. Environmental Protection Agency, 2001). If Congress should reinstate the tax credit for CBM, it would accomplish the following: (1) provide additional natural gas supplies to meet the national goals of the Clean Air Act; (2) help control future emissions; (3) make more gas available to consumers at a lower price; (4) assist operators; and (5) expand the national natural gas resource base to improve energy independence and security.

ASSESSMENT OF POTENTIAL IN PENNSYLVANIA

Correlations presented in Appendix 3 and throughout the literature show that the gas content of Pennsylvania's bituminous coal is directly related to rank and depth. For example, the higher the rank, the greater adsorptive capacity of the coal. However, within different ranks of coal, there will be variations in gas content based on variations in the coal chemistry (Appendix 2). For example, gas content varies inversely with the grade of coal or the inorganic (ash) content. That is, the higher the ash content, the lower the gas content. Although the coal type (maceral and lithotype composition) was not determined for the samples in this study, type affects porosity and permeability. Adsorbed methane is highest in the cleat-rich liptinites and vitrinites, and free methane is highest in the inertinites. Also, the physical nature of the coal dictates the rate of gas release. Friable coals having a more pronounced fracture network emit more gas during desorption than a blocky, dense coal. There was no apparent correlation between gas content and thickness, temperature, or barometric pressure in this study.

The greater the depth of overburden, the higher the methane content. This is related to the fact that deeper mines have higher emission rates and that rank increases with increasing depth. Nationally, a depth between approximately 500 and 3,500 feet is considered the optimum economic depth. In Pennsylvania, most identified coal beds between 500 and 2,000 feet deep are optimum targets. Thickness of coal penetrated (or multiple thin coals) is also important for economic production of CBM. Numerous relatively thick coal beds are favorable; however, one or two seams may well prove to be profitable. In the Northern Appalachian coal basin, a thickness of 1 foot is low but acceptable if part of a multiseam project. The combined production from multiple coal beds in a single well is comparable to the production from an individual seam that has a thickness equal to that of the multiple beds.

The presence of a fracture or cleat system in the coal bed is necessary for establishing permeability and hydrostatic conditions. It is commonly necessary to complete wells in areas where coals have natural fractures other than cleats. These may be faults, fold-induced fractures, or stress fractures due to the differential compaction properties of coal beds and adjacent shales. According to Ayers and Kelso (1989), subsurface fractures have been predicted by mapping lineaments on aerial photographs and comparing the trends with fractures in outcrops and cores. Favorable geologic structure and permeability are found on the flanks of anticlines or synclines, where the orientation and degree of jointing are more evident than on the structural axes.

CBM reservoir pressure is controlled by hydrostatic head. Highly permeable coal beds must be dewatered first before any significant gas flow by desorption can occur, since the methane is adsorbed on the surface of the coal and bound by reservoir pressure (McKee and others, 1984). By dewatering the seam via vertical boreholes, reservoir pressure is reduced and water saturation is lowered (Trevits and Finfinger, 1985). This raises the permeability and degree of gas saturation of the coal bed, enabling gas to flow freely to the well bore (Kissell and Edwards, 1975). According to the USBM, sufficient gas content within a coal bed should be at least 150 to 200 cf/t.

The first data set of this study shows that there is a correlation between depth and total gas content of the bituminous coal beds. In addition, these data indicate a fairly linear correlation between time and cumulative gas. These results should be taken into account when searching for economic deposits of CBM. Methane contents for anthracite are known to be either anomalously high or low, but production rates have been found to be low with or without artificial stimulation due to the lack of a well-developed fracture system. Based on the data available, economic potential in the anthracite area appears to be poor; however, more drilling should be done to determine if there are localized pockets that would be conducive to development.

Based on aggregate data from the second data set, available from Pennsylvania Geological Survey exploration drilling, from results directly from industry, and from the USBM (Diamond, LaScola, and Hyman, 1986), 24 coals (21 bituminous and 3 anthracite) have relatively large gas contents, greater than or equal to 125 cf/t (Table 4). The bituminous coals, in descending order, are Washington, Waynesburg "B," Upper Waynesburg, Lower Waynesburg, Uniontown, Sewickley, Redstone, Pittsburgh rider, Pittsburgh, Harlem, Upper Bakerstown, Brush Creek, Mahoning, Upper Freeport, Lower Freeport, Upper Kittanning, Middle Kittanning, Lower Kittanning, Clarion, Brookville, and Mercer; the anthracite coals, in descending order, are Tunnel, Peach Mountain, and Seven Foot leader. Depths range from 340 feet in the Uniontown coal of Washington County to 1,417 feet in the Freeport coal (name as reported) of Greene County. The highest gas contents, greater than or equal to 300 cf/t, are in the following five seams (two bituminous and three anthracite): Middle Kittanning(?), Lower Kittanning, Tunnel, Peach Mountain, and Seven Foot leader at depths ranging from 575 feet in the Lower Kittanning of Indiana County to 1,060 feet in the Lower Kittanning of Westmoreland County (Table 5).

The target area for commercial development in Pennsylvania is an elliptical-shaped region (outlined in Figure 1) in the southwestern part of the state, including most of Greene County and parts of Washington, Fayette, Allegheny, Westmoreland, Armstrong, Indiana, and Cambria Counties. This is where the deepest bituminous coal beds occur compared to other parts of the state. Pennsylvania's 27 CBM pools are also located within this target area. Overall estimates of CBM resources indicate that there may be 61 Tcf contained in the Northern Appalachian coal basin (which includes Pennsylvania, Ohio, West Virginia, and a small part of Maryland), 51 Tcf in southwestern Pennsylvania and northwestern West Virginia, and 2,654 Bcf (including methane from anthracite) in Pennsylvania. The deepest coals that exist here, such as the Allegheny Formation coals and other coals near mines having known high emission rates, are attractive to the developer. The relatively high rank, total effective coal thickness, and deep burial of the coal indicate that this area has great potential for production. Based on current data, the Pottsville Formation will be insignificant in its contribution to the CBM resource in the basin and perhaps in Pennsylvania. More exploration will verify whether this is true.

SUMMARY AND CONCLUSIONS

Historically, in the Northern Appalachian coal basin, CBM has endured a negative reputation in the mining industry coupled with neglect by the oil and gas industry. However, in about the last 20 years, interest in the economic value of coal-seam gas has attracted the oil and gas industry. In the 1970s, the MRCP, the USBM, and the USDOE developed a series of pilot methane-recovery projects whose success paved the way for future projects.

Significant geological factors affecting CBM gas flow and field development are as follows: (1) structural controls and tectonic history; (2) natural fracture networks on the flanks of anticlines and synclines; (3) favorable coal rank (thermal history), grade, type, and physical nature of the coal; for example, fractured, low-ash bituminous coal; (4) depositional and stratigraphic controls and traps; rock units or features that may or may not hinder the flow of methane; (5) hydrologic controls; hydrostatic head governs CBM reservoir pressures; and (6) the present state of in situ stress; by reducing the pressure and releasing the gas in a coal bed, the physical state of the reservoir is brought into equilibrium, which raises the permeability of the coal bed and allows for easier gas flow to the well bore. For a successful CBM production project, reservoir characterization must be combined with geologic characterization and production engineering.

For the first data set of this study, cores from various coal beds in Armstrong, Cambria, Greene, and Somerset Counties were tested for their gas content. Supplementary data were acquired from industry in Fayette and Westmoreland Counties. For the second data set, results from these tests were compiled with additional data from the MRCP, the USBM, and the USDOE. Graphs were plotted for comparisons and trends. Analyses of coal-bed depth and thickness versus total gas content revealed that there is a direct correlation between depth and gas content. Coal thickness, which is important in planning for commercial development, did not show a direct correlation with gas content in this study. However, this does not mean that no correlation exists. It must be advised that depth alone is not the sole indicator of high gas content. Other graphs show a fairly linear correlation between time and cumulative gas. For the new coal core samples tested by the Pennsylvania Geological Survey, gas contents ranged from 9 cf/t for the Upper and Lower Kittanning seam in Armstrong County to 298 cf/t for the Lower Freeport seam in Cambria County. Additional graphs were generated to determine relationships between depth and thickness, respectively, versus total gas content by coal rank and roof lithology.

Steeply dipping and distorted coal beds complicate the scenario for favorable commercial development in the Anthracite region. Methane contents for anthracite can be anomalously high or low, but because of the lack of a well-developed fracture system, production rates have been found to be low. Based on available data, the economic potential in this area appears to be poor; however, more drilling could help determine if there are localized pockets of methane that could be developed.

The target area for commercial development in Pennsylvania is a roughly elliptical-shaped region in the southwestern part of the state. The Pittsburgh and deeper coals that exist here are attractive to the developer. These coals have great potential for production because of their relatively high rank, total effective thickness, and deep burial. Overall estimates of CBM resources indicate that there may be 61 Tcf contained in the Northern Appalachian coal basin, 51 Tcf in southwestern Pennsylvania and northwestern West Virginia, and 2,654 Bcf (including methane from anthracite) in Pennsylvania. Cooperation between the gas producer and coal owner is necessary in cases of separate ownership and leases. The developer must carefully evaluate the technical, economic, political, and legal aspects, which are critical parts of planning a project in the Northern Appalachian coal basin.

The optimal criteria for locating favorable drilling sites for CBM in Pennsylvania are the following:

1. Numerous relatively thick, high-rank coal beds; however, one or two seams may be just as economic as multiple seams, depending on their gas content.

2. Sufficient gas content within an individual coal bed, 125 to 150 scf/t.
3. Sufficient depth or overburden thickness, at least 500 feet below the water table; in Pennsylvania, most identified coal beds between 500 and 2,000 feet deep are optimum targets.
4. Favorable geologic structure, permeability, and porosity, especially fracture permeability on the flanks of anticlines or synclines; permeabilities ranging from 0.1 to 0.5 md.
5. Sufficient reservoir pressure and gas saturation, 125 to 175 psia of pressure.
6. Stratigraphic traps to maintain reservoir integrity and minimize ambiguities in source rock identification for ownership purposes.
7. Unmined coal seams or seams that are a significant distance away from the outcrop or active mining to minimize loss of methane due to migration to the surface.

Results from horizontal drill holes show that drilling perpendicular to the direction having the highest concentration of face cleats will yield 2.5 to 10 times as much gas as holes drilled at right angles to the secondary or butt cleat. More importantly, the highest permeabilities (directional permeability) providing good gas flow are parallel to the face-cleat orientation. Maximum gas production can be achieved after the highly permeable reservoir has been drained of water. The size of the drainage radius, which is a function of fracture permeability, is also critical in the commercial development of CBM.

Coal in general is an ideal reservoir rock. Its retention capacity is superior to that of a conventional natural gas sandstone or carbonate reservoir. Different ranks of coal have different capacities to store gas. In most cases, higher rank (and deeper) coals have a higher adsorptive or retention capacity for methane-gas storage than lower rank coals. The exception is anthracite, from which production rates have been found to be low with or without artificial stimulation.

Some of the reasons why Pennsylvania CBM should be used are the following: (1) a conservative estimate of natural gas recoverable from bituminous and anthracite coal beds totals 2,654 Bcf, of which well over half is classified probable and possible; (2) known coal-bed locations yield low exploration costs; (3) proximity to a pipeline infrastructure; (4) low capital investment due to the relatively shallow depths versus conventional reservoir depths; and (5) the gas can be used for the natural gas pipeline, electric power generation, cogeneration plants, and public utilities instead of wasteful venting to the atmosphere, which contributes to the array of suspicious greenhouse gases.

If Congress should reinstate the tax credit for CBM it would provide the following advantages: (1) additional natural gas supplies to meet the national goals of the Clean Air Act; (2) help to control future emissions; (3) more gas availablity to consumers at a lower price; (4) assistance to operators; and (5) expansion of the national natural gas resource base to improve energy independence and security.

A resolution was sought from the legislature asking the Department of Interior to delete Pennsylvania as an affected state. The coal and oil and gas industry boards concluded that current oil and gas statutes are sufficient to address CBM issues. No agreement was reached between the coal and oil and gas industries on the ownership issues. There is still no ideal method that satisfies all participants, just ways to circumvent the ownership problem. The forced pooling mechanism does not address extraction-related conflicts that exist when noncoal owners have a right to develop CBM. Its success depends on the feasibility of regulating these conflicts. Some attorneys strongly advise a system of compulsory negotiation that results in binding arbitration.

When mineral ownership rights are not established among different parties for a particular coal estate, there is potential for conflict. Several options exist to address this issue. These include requiring the CBM lessee to designate proposed wells and obtain the coal owner's approval, as required by state law; or the CBM lease should specifically address the issue of conflicting uses and ownership on a case-by-case basis title search and analysis. Any successful development will depend on compromises between the oil and gas developer, the landowner, and the coal company. Despite these barriers, Pennsylvania continues to experience growth in the CBM industry.

RECOMMENDATIONS FOR FUTURE STUDIES

Suggestions for recommendations evolved from previous CBM studies with the West Virginia Geological and Economic Survey (Bruner and others, 1995; Schwietering and others, 1991). Much research and cooperative efforts are needed to determine and/or develop the following: the CBM resource in the basin; the factors critical to locating and developing prospect areas (including contacting drilling companies for geophysical logs for a comprehensive subsurface analysis of structure and stratigraphy); the best strategies for completing wells; methane recovery and mining system integration; cofiring and combustion optimization; and extraction/utilization projects.

More information is needed about coal quality, (part of which includes variations in rank and grade of the coal and types of macerals in the coals), total gas content, residual gas content, desorption rates, gas fractional analyses to determine contamination levels, permeability, and hydrologic properties. Research should also be done to find ways to recover the residual gas in the coal beds more quickly than the rate that occurs naturally.

Additional structural analyses of the folds, faults, cleats and other fractures, and lineaments are needed to better determine the effect these features have on the formation of traps for CBM. Structural analyses should include evaluations of magnetic and gravity surveys to locate areas where movements along faults bounding Precambrian basement blocks may have influenced the formation of CBM targets.

To further define production potential, it is important to know more about the hydrodynamics of the reservoir or basin in general. According to Pashin and others (1990), some of the parameters important to CBM production are: (1) water production, which indicates the degree of fluid pressure; (2) fluid pressure, which controls methane adsorption in the coalbed reservoir; (3) flow-pattern anomalies, which may be an indicator of high CBM production areas; and (4) water chemistry, a concern in CBM development that can also be an indicator of high production areas.

As noted by Lewin (1995), government-supported research should begin developing technology for safe flaring of methane from degasification wells. Although mandatory technological controls will probably play a limited role in CBM emission regulation, one type of standard may be implemented to limit emissions from coal mines. Even if the gas is not used as a resource, flaring of the gas is preferable to venting because of the potency of methane as a greenhouse gas as opposed to carbon dioxide. Mandatory flaring could reduce methane emissions by approximately 1 teragram (Tg) (52.6 Bcf at sea level) (Lewin, 1995).

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GLOSSARY

Activation energy. The extra amount of energy that any particle or group of particles must have to go from one energy state into another, as in phase and movement of particles in diffusion.

Adsorbate density. The density of an adsorbed substance.

Adsorption. The adhesion in an extremely thin layer of molecules (gases, solutes, or liquids) to the surfaces of solid bodies or liquids with which they are in contact.

Adsorption (sorption) isotherm. A laboratory measurement of the gas storage capacity in a coal bed as a function of pressure and constant temperature; this test involves subjecting a representative coal sample to pressures and temperatures simulating in situ stress in a CBM reservoir.

Alginite. A maceral of coal in the exinite group, consisting of algal matter and characteristic of boghead coals.

Alkane (paraffin) series. Hydrogen-saturated, straight-chain compounds of the paraffin or aliphatic hydrocarbon series containing only single bonds. An alkane has a continuous chain if each carbon atom in its molecule is joined to at most two other carbon atoms; it has a branched chain if any of its carbon atoms is joined to more than two other carbon atoms. The empirical formula for the alkane series is C_nH_{2n+2}, and the simplest member is the continuous-chain alkane methane (CH_4). Chemically, the alkanes are relatively unreactive and are used extensively as fuels.

Alkene (olefin) series. Unsaturated (undersaturated in hydrogen), straight-chain compounds of the olefin hydrocarbon series containing at least one carbon-carbon double bond per molecule (olefinic linkage). The empirical formula is C_nH_{2n}, and the simplest member is ethene ($H_2C{=}CH_2$). This series is more chemically reactive than the alkane (paraffin) series; it is readily produced in refinery cracking processes and is important in the petrochemical industry.

Angstrom. A unit of length equal to 1 ten billionth of a meter, used especially to measure wavelengths of light, or, for this study, the diameter of the micropores of coal.

Anthraxylon. A composite term for the vitreous coal components derived from woody tissues of plants and forming lustrous bands interlayered with dull attritus in banded coal.

Aromatic (benzene) series. Monocyclic or polycyclic, relatively stable compounds of the unsaturated hydrocarbon series having a strong or aromatic odor and alternating carbon-carbon double bonds and single bonds. The empirical formula is C_nH_{2n-6}, and the simplest member is benzene (C_6H_6). The compounds of higher molecular weight in this series are solid and may fluoresce or be slightly colored.

Attrital coal. A coal in which the ratio of anthraxylon to attritus varies from 1:1 to 1:3. The groundmass or matrix of banded coal, in which vitrain and commonly fusain are embedded.

Attritus. A composite term for dull gray to nearly black coal components of varying maceral content, unsorted and having fine granular texture, which form the bulk of some coals or are interlayered with bright bands of anthraxylon in others. This material is composed of a tightly compacted mixture of altered vegetal materials, especially those that were relatively resistant to complete degradation.

Biogenetic (biogenic) stage. A part of the coalification stage where bacterial degradation of base organic material to peat occurs.

Boghead coal. A sapropelic coal resembling cannel coal in its physical properties but consisting dominantly of algal matter rather than spores.

British thermal unit (Btu). Quantity of heat (about 252 calories) required to raise the temperature of 1 pound of water 1 degree Fahrenheit at a specified temperature.

Butane (C_4H_{10}). A gaseous, inflammable paraffin (alkane) hydrocarbon occurring in petroleum and natural gas in either of two isomeric forms: n-butane (n-C_4H_{10}) or isobutane (i-C_4H_{10}).

1-butene (C_4H_8). An unsaturated olefin (alkene) hydrocarbon containing double bonds between two or more carbon atoms. If hydrogen or other elements are not available to react with the unsaturation, some olefins will react with themselves to form high-molecular-weight polymers.

Butt cleat. A short, poorly defined joint or cleavage plane in a coal bed oriented at right angles to the longer face cleat and terminating against it.

Cannel coal. A compact, tough, relatively uncommon sapropelic coal (derived from organic residues in stagnant water; undergoes putrefaction under anaerobic conditions) that consists dominantly of spores and is characterized by dull to waxy luster, conchoidal fracture, and massiveness. It is attrital and high in volatiles; by American standards it must contain less than 5 percent anthraxylon.

Catagenetic (geochemical) stage. A part of the coalification process that includes a complex series of chemical reactions catalyzed by increased temperature and pressure conditions (due to thicker overburden or higher geothermal gradients) that are much different from those of deposition.

Cellulose. A polymeric carbohydrate composed of glucose units, whose formula is $(C_6H_{10}O_5)x$, of which the permanent cell membranes of plants are formed, making it the most abundant carbohydrate.

Channel sandstone. A sand originally deposited in a stream bed or other channel that is now a sandstone.

Clay vein. A body of clay, usually roughly tabular in form like a dike or vein, that fills a crevice in a coal seam; it originates where the clay from the roof or floor has been forced into a small fissure, commonly altering or enlarging it.

Cleat. A joint or set of joints in a coal bed where the coal is fractured. The two cleat sets are developed perpendicular to each other.

Coal-mine methane. The methane contained in the coal and surrounding strata that may be released as coal mining proceeds. In some instances, methane that continues to be released from the coal-bearing strata once a mine is closed and sealed may also be referred to as coal-mine methane because the liberated methane is associated with a coal mine.

Cogeneration. The simultaneous generation of electrical energy and low-grade heat from the same fuel.

Concentration gradient. Rate of variation in concentration of a substance in a given direction in space at a fixed time.

Conversion well. A gob ventilation borehole converted to a gob production well.

Cumulative gas. The total amount of gas in a coal sample measured during desorption; this value is used in a formula for the total gas content (see *total gas content*).

Cutinite. A maceral of coal in the exinite group, consisting of plant cuticles.

Darcy's law. A derived formula for fluid flow based on the assumption that the flow is laminar and inertia can be neglected (in gas flow, the velocity of the flow is proportional to the pressure gradient multiplied by the ratio of permeability multiplied by the density divided by the gas viscosity). In CBM flow dynamics, once the gas has migrated into larger pores and into the cleat and fracture system, it will then flow into the well bore or mine due to a pressure gradient.

Décollement. A shallow-dipping to subhorizontal detachment surface in strata, resulting in independent styles of deformation in the rocks above and below.

Degasification. A system that degasifies a mine, such as extraction of methane gas from a pre-mining drill hole. Technically, the term most commonly refers to removal of methane by drainage technology.

Demethanation. The splitting off of methyl side chains followed by their saturation.

Desorption. A process in which adsorbed material (such as gas) is removed from the adsorbent; in the USBM direct method used in this report, the desorbed gas is the total volume of gas emitted from a coal core sample, determined by measuring the amount of water displaced by the gas in a graduated cylinder. This value is used along with the values for lost gas, residual gas, and sample weight determinations to estimate the total gas content of the sample, commonly measured in cubic feet per ton of coal.

Diagenesis. All the chemical, physical, and biological changes undergone by a sediment after its initial deposition and during and after its lithification, exclusive of surficial alteration (weathering) and metamorphism.

Diffusion. In CBM flow dynamics, the transport of gas through micropores of the solid coal matrix due to a concentration gradient.

Diffusion coefficient. The measure of the transport of gas through micropores of the solid coal matrix due to a concentration gradient.

Directional permeability. In coal, a variation in the degree of permeability, or capacity for fluid transmission, due to the cleat or natural fracture system; permeability is a function of effective stress and the ratio of initial fracture porosity to matrix compressibility (fracture closure pressure).

Drainage radius. The characteristic radius to the outer drainage boundary of a reservoir or field.

Dry, ash-free basis. Coal analyses are calculated to the dry, ash-free basis by adjusting formulas used in calculations in order to deduct the weight of ash from the total coal, because this is the simplest way to compare organic fractions of coal without the diluting effects of inorganic components. When whole coal is burned, it will generally yield 1,000 to 3,000 Btu/lb less than the dry, ash-free value.

Empirical relationship. Based on experience or observation alone, commonly without due regard for system and theory.

Ethane (C_2H_6). A colorless, odorless, water-insoluble, gaseous paraffin (alkane) hydrocarbon that occurs in natural gas or can be produced as a by-product in the cracking of petroleum.

Ethylene (C_2H_4). An unsaturated olefin (alkene) hydrocarbon containing double bonds between two or more carbon atoms.

Exine. The outer, very resistant layer of the two major layers forming the wall (sporoderm) of spores and pollen, consisting of sporopollenin and situated immediately outside the intine. It is divided into two layers (ektexine and endexine) based on staining characteristics.

Exinite. A coal maceral group including sporinite, cutinite, alginite, resinite, and liptodetrinite, derived from spores, cuticular matter, resins, and waxes. Exinite is relatively rich in hydrogen.

Face cleat. The major well-defined joint or cleavage plane in a coal bed.

Fick's law. A mathematical model that describes the diffusion of methane through the micropores of the solid coal matrix due to a concentration gradient.

Field. A group of pools related to a single geologic feature, either structural or stratigraphic.

Fixed carbon. The solid, combustible material remaining after removal of moisture, ash, and volatile matter in coal, coke, and bituminous materials (expressed as a percentage).

Flowback. The amount of proppant that tends to clog up the well bore during artificial stimulation of low-permeability CBM reservoirs. Proppant flowback usually occurs during the early cleanup and dewatering stages of a CBM well.

Fracture porosity. Porosity resulting from the presence of openings produced by the breaking or shattering of an otherwise less pervious rock.

Friability. The ability of a coal to crumble naturally or easily upon handling. Friability relates to depth of the sample below the surface, fixed carbon percentage, Hardgrove grindability index, and proximity to tectonic disturbance.

Gas chromatography. A process for separating gases or vapors from one another by passing them over a solid (gas-solid chromatography) or liquid (gas-liquid chromatography) phase. The gases are repeatedly adsorbed and released at differential rates, resulting in separation of their components.

Gob. A fractured zone of coal and surrounding strata above the coal that has relaxed and collapsed during longwall mining; this gob area is a rich source of methane.

Gob gas. The gas emitted from the fractured zone of coal and surrounding strata above the coal that has collapsed during longwall mining; the heating value of gob gas ranges from 300 to 800 Btu/cf.

Hardgrove grindability index. The ease with which coal can be pulverized before being fed into the combustion chamber, or the structural strength of coal or coke; this value is calculated from the mass of fine material produced after a given mass of coal is ground in a Hardgrove mill.

Homologous. Belonging to or consisting of a chemical series whose members have a regular difference in composition of one carbon and two hydrogen atoms, CH_2.

Hydraulic fracture stimulation (fracing). A general term, for which there are numerous trade or service names, for the fracturing of rock in an oil or gas reservoir by pumping in water (or other fluid) and sand under high pressure. The purpose is to produce artificial openings in the rock to act as flow channels and increase permeability. The pressure opens cracks and bedding planes, and sand introduced into these cracks serves to keep them open when pressure is reduced.

Hydrostatic head. The height of a vertical column of water whose weight, if of unit cross section, is equal to the hydrostatic pressure at a given point.

Hydrostatic pressure. The pressure exerted by the water at any given point in a body of water at rest.

Inertinite. A coal maceral group including micrinite, macrinite, sclerotinite, fusinite, semifusinite, and inertodetrinite. These substances are characterized by a relatively high carbon content and a reflectance higher than vitrinite. They are relatively inert during the carbonization process.

In situ stress. The force (reservoir pressure and overburden pressure) per unit area acting on the reservoir and expressed as pounds or tons per square inch or dynes or kilograms per square centimeter.

Intine. The thin inner layer of the two major layers forming the wall (sporoderm) of spores and pollen; it is composed of cellulose and pectates, is situated inside the exine, and surrounds the living cytoplasm.

Isotope. One of two or more species of the same chemical element having the same number of protons in the nucleus, but differing from one another by having a different number of neutrons. Owing to their mass differences, the isotopes of an element have slightly different physical and chemical properties, by which they can be separated.

Kiel hydraulic fracture stimulation. A service name for the fracturing of rock in an oil or gas reservoir by pumping in water (or other fluid) and sand under high pressure. (See "Hydraulic fracture stimulation.")

Laminar flow. The flow of homogeneous fluids (liquids or gases) through porous media of uniform packing and cross section; based on Darcy's law.

Liptinite (exinite). A hydrogen-rich coal maceral group including sporinite, cutinite, alginite, resinite, and liptodetrinite, derived from spores, cuticular matter, resins, and waxes.

Liptodetrinite. A maceral of coal in the exinite group, having no recognizable structure and low reflectance and fluorescence; because of its finely detrital condition it cannot be assigned with certainty to any of the other macerals of the group.

Lithotype. A macroscopically visible band in humic coals, analyzed by physical characteristics rather than by botanical origin.

Longwall mining. A method of underground mining in flat-lying strata, especially of coal, where parallel entries are driven into the seam to the limit of the block to be mined; from the end of these entries, workings are driven at right angles in both directions. A longwall face is produced as these workings are widened back toward the point of entry. Working space is provided by timbers or other supports; the roof caves as mining progresses. Almost all of the coal or other desired mineral is recovered, in contrast to the room-and-pillar method.

Maceral. One of the organic constituents that comprise the coal mass; all petrologic units seen in polished or thin sections of coal. Macerals are to coal as minerals are to inorganic rock.

Major/minor coals. A coal designation that indicates the degree of economic importance, as far as thickness and minability are concerned, on a local or regional basis.

Methane (CH_4). A colorless, odorless, nontoxic (not toxic when inhaled, but it can produce suffocation by reducing the concentration of oxygen inhaled) and flammable gas; the simplest member of the alkane (paraffin) hydrocarbon series. It is the principal constituent of natural gas and can be formed from thermal decomposition of sedimentary organic matter or by bacteria; it is found associated with crude oil and coal.

Methane drainage. A system that drains methane from coal seams and/or surrounding rock strata. These systems include vertical pre-mine wells, gob wells, and in-mine boreholes.

Methane emissions. The total amount of methane that is not used and is therefore emitted to the atmosphere. Methane emissions are calculated by subtracting the amount of methane used from the amount of methane liberated.

Methane liberated. The total amount of methane released, or liberated, from coal and surrounding strata during the mining process. The total is determined by summing the volume of methane emitted from the ventilation system and volume of methane that is drained.

Millidarcy. The customary unit of measurement of fluid permeability, equivalent to 0.001 darcy.

Mineral-matter-free basis. Coal analyses are calculated to a mineral-matter-free basis by adjusting formulas used in calculations in order to deduct the weight of mineral matter from the total coal. Mineral matter in coal (which is also the parent material for coal ash) is derived from minerals in the original plant material that formed coal, or from extraneous sources such as sediments and precipitates from mineralized water.

Orbiculoid. Circular or spherical in shape, as used to describe the configuration of brackish-water or marine brachiopods and gastropods.

Pectate. Any of various water-soluble substances that bind adjacent cell walls in plant tissues and yield a gel that is the basis of fruit jellies.

Pentane (C_5H_{12}). Any of three isomeric, low-boiling paraffin (alkane) hydrocarbons found in petroleum and natural gas.

Perforation. The puncturing of a well casing opposite an oil- or gas-bearing zone to permit oil or gas to flow into a cased borehole.

Polymer. A chemical compound or mixture of compounds formed by a chemical reaction in which two or more molecules combine to form larger molecules that contain repeating structures.

Polymeric. Relating to or constituting a polymer.

Pool. A body of oil or gas or both occurring in a separate reservoir and under a single pressure system; the simplest unit of commercial occurrence.

Pounds per square inch absolute (psia). The amount of pressure exerted on a fluid/gas reservoir, measured in force per unit area exerted by the fluids against the face of the reservoir rock where it has been penetrated by a well. The abbreviation "psi" commonly means the same as "psig," pounds per square inch gage; psia is a conversion of psi and psig and is determined by adding the value of atmospheric pressure at the ground surface.

Pressure gradient. The rate of variation of pressure in a given direction in space at a fixed time.

Pressure-transient well test. A reservoir test used to establish and quantify characteristics governing the flow of fluid (flow rates, rate fluctuations, stabilizations, and pressures) in the immediate vicinity of the tested well or within its particular drainage radius. Tests are typically conducted for a single well completion in a well, but multiple well completions in a well may be tested as part of a single well pressure-transient test.

Propane (C_3H_8). An inflammable, gaseous paraffin (alkane) hydrocarbon of the methane series. It occurs naturally in crude petroleum and natural gas. It is also produced by cracking and is used primarily as a fuel and in the making of chemicals.

Proppant. A material, commonly sand, injected along with water (or other fracturing fluids) into the CBM reservoir to provide mechanical support to hold open the fractures created during hydraulic stimulation.

Propylene (C_3H_6). An unsaturated, olefin (alkene) hydrocarbon containing double bonds between two or more carbon atoms.

Putrefaction. The decomposition of organic matter by slow distillation in the presence of water and without air. Methane and other gases (H_2, NH_3, H_2S) are formed.

Reservoir pressure. The pressure in a reservoir that existed before the natural equilibrium of the formation was disturbed by any production; it can be measured by the force per unit area exerted by formation fluids against the face of the reservoir rock where it has been penetrated by a well.

Resinite. A maceral of coal in the exinite group, consisting of resinous compounds commonly in elliptical or spindle-shaped bodies representing cell-filling matter or resin rodlets.

Rider. A thin seam of coal overlying a thick one.

Roof. The rock immediately above a coal seam. The roof is commonly a shale and may be carbonaceous and softer than rocks higher up.

Room-and-pillar mining. A system of mining in which the ore is mined in rooms separated by pillars of undisturbed rock left for roof support.

Sapropelic coal. Coal that is derived from organic residues (finely divided plant material, spores, and algae) in stagnant water. Putrefaction under anaerobic conditions, rather than peatification, is the formative process. The main types of sapropelic coal are cannel coal, boghead coal, and torbanite. Sapropelic coals are high in volatiles and generally dull, massive, and relatively uncommon.

Saturated hydrocarbons. The alkane (paraffin) series of hydrocarbons that have the valence of all their carbon atoms satisfied by single bonds. They are chemically less reactive than the alkene/olefin series (the unsaturated hydrocarbons) because the outer electron shells of the carbon and hydrogen atoms have been filled by the sharing of electron pairs.

Seam. A bed, vein, or series of beds of coal.

Severed coal title. A title or deed that distinguishes coal from other parts of the estate, such as the surface, the oil and gas, the CBM, and others. The severance deed that created the separate estates may have conveyed or reserved the natural commodities present as "minerals." A developer should review case law in that jurisdiction to determine if CBM is included within the term "minerals" and contact the appropriate entity for a CBM lease.

Shut in. A temporary (up to five years) halt in well production. This status is granted providing the operator can prove future well utility. Shut-in pressures, or reservoir pressures at the wellhead, are measured when the valves are closed.

Specific emissions. The total amount of methane liberated per ton of coal mined; an important indicator of whether a mine is a good candidate for a methane recovery project.

Sporinite. A maceral of coal in the exinite group, consisting of spore exines that are generally compressed parallel to the stratification.

Synclinorium. A composite synclinal structure of regional extent composed of lesser folds.

Torbanite. Essentially synonymous with boghead coal, but commonly considered a highly carbonaceous oil shale. It is named from its type locality, Torbane Hill, in Scotland.

Total gas content. The gas content-in-place of a coal seam is determined by adding the value of gas lost during coring (L) to the cumulative gas measured during desorption (D), dividing that by the sample weight (SW), then adding the amount of residual gas in the coal (R), or [([L + D]/SW) + R].

Unsaturated hydrocarbons. The alkene (olefin) and aromatic series of hydrocarbons containing carbon-carbon double bonds having fewer than four hydrogen atoms attached to each carbon atom; this series is more reactive than the saturated hydrocarbons.

Ventilation. A system used to control the concentration of methane within mine working areas, consisting of powerful fans that move large volumes of air through the mine to dilute methane concentrations.

Ventilation emissions. Methane released to the atmosphere from ventilation systems in very low concentration (typically less than 1 percent in air). Methane emission rates at each coal mine are tested quarterly.

Vitrain. Bright, homogeneous bands of coal having a conchoidal fracture.

Vitrinite. A coal maceral group that is characteristic of vitrain and is composed of humic material.

Vitrinite reflectance. A quantitative measurement of coal rank and thermal maturity based on the percentage of light reflectance from the polished surface of the coal; specifically, reflectance of a vitrinite maceral (measured microscopically in immersion oil) when illuminated with plane-polarized (white) light. Vitrinite reflectance values vary systematically with fixed carbon content and are widely used as a thermal maturity indicator.

ABBREVIATIONS

Å	angstrom
Bcf	billion cubic feet
Bcf/mi^2	billion cubic feet per square mile
Bcfy	billion cubic feet per year
Btu	British thermal unit
Btu/cf	British thermal unit per cubic foot
Btu (daf)	British thermal unit (dry ash-free basis)
Btu/lb	British thermal unit per pound
Btu/scf	British thermal unit per standard cubic foot
°C	degree Celsius
cc	cubic centimeter
cc/g	cubic centimeters per gram
cf/t	cubic feet per ton
°F	degree Fahrenheit
ft^2/lb$_m$	square feet per pound of matrix
g	gram
m^3	cubic meter
Mcfd	thousand cubic feet per day
md	millidarcy(ies)
MMBtu	million British thermal units
MMcf/acre	million cubic feet per acre
MMcfd	million cubic feet per day
MMty	million tons per year
psia	pounds per square inch absolute
psig	pounds per square inch gage
scf/t	standard cubic feet per ton
STP	standard temperature and pressure
Tcf	trillion cubic feet
Tg	teragram

FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM UNITS (SI)

Multiply inch-pound units	*By*	*To obtain SI units*
	Length	
inch (in.)	2.540	centimeter (cm)
foot (ft)	.3048	meter (m)
mile (mi)	1.6093	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
barrel (water) (bbl)	.11924047	cubic meter (m^3)
cubic inch ($in.^3$)	16.387	cubic centimeter (cc)
cubic foot (ft^3)	.02832	cubic meter (m^3)
billion cubic feet (Bcf) (at sea level)	.019011407	teragram (Tg)
cubic foot per ton (short) (cf/t)	.031214	cubic centimeter per gram (cc/g)
	Temperature	
degree Fahrenheit (°F)	°C = 5/9 (°F−32)	degree Celsius (°C)
	Energy and work	
British thermal unit (Btu)	1054.35	joule (j)
British thermal unit (Btu)	.000293	kilowatt hour (kWhr)
British thermal unit per pound (Btu/lb)	2.32444	joule per gram (j/g)
	Mass/weight	
ton (short) (t)	.9072	metric ton (t)
ton (short) (t)	907.1847	kilogram (kg)
	Pressure and stress	
pound per square inch (psi)	703.1	kilogram per square meter (kg/m^2)
	Fluid permeability	
millidarcy (md)	9.869233×10^{-16}	square meter (m^2)

APPENDIX 1

GAS-CONTENT AND COAL

Table 6. *Total Gas Content and Coal Chemical Data for Coal Beds in Armstrong,*

County	Coal bed	Sample number	Total thickness of coal bed (feet)	Depth to base of coal bed (feet)	Total gas content of coal bed (cf/t)	Moisture (AR)[1]	Ash (AR)[1]	Ash (dry)	Volatile matter (AR)[1]	Volatile matter (dry)
Armstrong	Upper Kittanning	A1–1	1.29	275	13	1.52	15.83	—	—	—
do.	Lower Kittanning	A1–2a—2c	5.31	419	26	1.33	15.24	—	—	—
do.	Upper Kittanning	A2–1	2.29	132	9	1.86	12.60	—	—	—
do.	Lower Kittanning	A2–2a—2b	3.98	257	9	1.58	18.34	—	—	—
Cambria	Upper Freeport (top, 0.21 ft)[4]	B1–1a	[5]5.27	[5]724	[5]156	.63	9.44	9.50	20.96	21.09
do.	Upper Freeport (middle, 2.5 ft)[4]	B1–1b				.93	9.33	9.41	21.25	21.45
do.	Upper Freeport (bottom, 1.33 ft, extremely shaly)[4]	B1–1c				—	—	—	—	—
do.	Lower Freeport (top, 0.54 ft)[4]	B1–2a	[5]2.77	[5]771	[5]298	.79	9.86	9.93	19.80	19.96
do.	Lower Freeport (bottom, 0.21 ft)[4]	B1–2b				.63	9.32	9.38	21.16	21.29
Fayette	Lower Kittanning	C1	3.00	333	22.5	—	8.00	—	30.80	—
do.	do.	C2	4.58	417	139.6	—	44.30	—	22.90	—
do.	do.	C3–1	2.73	473	85.8	—	11.80	—	30.30	—
do.	Brookville	C3–2	3.29	547	214.9	—	24.10	—	—	—
do.	Lower Kittanning	C4–1	2.61	618	174.2	—	8.70	—	30.20	—
do.	Brookville	C4–2	3.88	695	256.6	—	17.30	—	—	—
do.	Lower Kittanning	C5	2.78	738	96.9	—	8.80	—	31.60	—
do.	do.	C6	2.69	791	170.8	—	9.90	—	32.50	—
do.	do.	C7	4.15	801	208.1	—	25.80	—	25.10	—
do.	do.	C8–1	2.50	845	233.7	—	8.90	—	29.50	—
do.	Clarion	C8–2	2.92	878	286.0	—	22.20	—	—	—
do.	Lower Kittanning	C9	4.16	856	257.5	—	23.40	—	29.10	—
do.	do.	C10	3.07	996	280.9	—	18.60	—	—	—
do.	Clarion	C11	2.61	380	10.9	—	15.90	—	—	—
do.	do.	C12	3.22	445	87.3	—	28.00	—	32.20	—
do.	do.	C13	3.21	1,090	206.2	—	18.50	—	31.20	—
do.	Brookville	C14	3.49	1,270	171.9	—	20.00	—	—	—
Greene	Waynesburg "A"	D1–1	—	510	51	—	—	—	—	—
do.	Waynesburg	D1–2	6.17	594	106	—	—	—	—	—
do.	Sewickley	D1–3	4.50	840	216	—	—	—	—	—
do.	Redstone	D1–4	.58	888	191	—	—	—	—	—
do.	Pittsburgh rider	D1–5	—	913	138	—	—	—	—	—
do.	Pittsburgh	D1–6	—	934	116	—	—	—	—	—
do.	Ten Mile (0.44 ft)[4]	D2–1	.83	351	30	1.29	18.93	19.18	38.41	38.91
do.	Little Washington (0.33 ft)[4]	D2–2	.85	610	85	1.29	13.75	13.93	36.01	36.48
do.	Waynesburg "A" (top, 0.60 ft)[4]	D2–3a	[5]1.40	[5]660	[5]75	.90	20.67	20.86	37.76	37.10
do.	Waynesburg "A" (bottom, 0.33 ft)[4]	D2–3b				.96	20.36	20.56	35.18	35.52
do.	Waynesburg (top, 0.44 ft)[4]	D2–4a	[5]6.17	[5]730	[5]76	.92	19.10	19.28	38.55	38.91
do.	Waynesburg (middle, 0.31 ft)[4]	D2–4b				1.27	12.77	12.93	39.51	40.02
do.	Waynesburg (bottom, 1.84 ft)[4]	D2–4c				1.47	17.61	17.87	36.14	36.68

CHEMICAL DATA

Cambria, Fayette, Greene, Somerset, and Westmoreland Counties

Volatile matter (daf)[2]	Fixed carbon (AR)[1]	Fixed carbon (dry)	Fixed carbon (daf)[2]	Sulfur (AR)[1]	Sulfur (dry)	Sulfur (daf)[2]	Btu (AR)[1]	Btu (dry)	Btu (daf)[2]	Apparent rank[3]
—	—	—	—	3.13	—	—	12,583	—	15,226	HV–A
—	—	—	—	3.81	—	—	12,744	—	15,278	HV–A
—	—	—	—	3.18	—	—	13,082	—	15,294	HV–A
—	—	—	—	4.10	—	—	12,176	—	15,206	HV–A
23.31	68.97	69.41	76.69	3.33	3.35	3.70	13,973	14,062	15,538	LV
23.68	68.49	69.14	76.32	3.13	3.16	3.49	13,947	14,078	15,542	LV
—	—	—	—	—	—	—	—	—	—	LV
22.16	69.55	70.11	77.84	1.95	1.96	2.18	13,901	14,012	15,557	LV
23.50	68.89	69.33	76.50	2.35	2.36	2.61	13,933	14,021	15,472	LV
33.50	61.20	—	—	1.85	—	—	14,087	—	—	HV–A
41.10	32.80	—	—	4.34	—	—	8,880	—	—	HV–A
34.40	57.90	—	—	4.00	—	—	13,279	—	—	HV–A
34.10	—	—	—	—	—	—	—	—	—	HV–A
33.10	61.10	—	—	1.70	—	—	14,178	—	—	HV–A
31.60	—	—	—	—	—	—	—	—	—	HV–A
34.60	59.60	—	—	2.64	—	—	—	—	—	HV–A
36.10	57.60	—	—	2.76	—	—	14,303	—	—	HV–A
33.60	49.60	—	—	1.30	—	—	11,309	—	—	HV–A
32.40	61.60	—	—	1.64	—	—	14,027	—	—	HV–A
34.70	—	—	—	—	—	—	—	—	—	HV–A
38.00	47.50	—	—	6.83	—	—	12,504	—	—	HV–A
30.80	—	—	—	—	—	—	—	—	—	HV–A
37.90	—	—	—	—	—	—	—	—	—	HV–A
37.20	55.20	—	—	2.84	—	—	13,473	—	—	HV–A
36.40	61.20	—	—	2.05	—	—	14,708	—	—	HV–A
34.10	—	—	—	—	—	—	—	—	—	HV–A
—	—	—	—	—	—	—	—	—	—	HV–A
—	—	—	—	—	—	—	—	—	—	HV–A
—	—	—	—	—	—	—	—	—	—	HV–A
—	—	—	—	—	—	—	—	—	—	HV–A
—	—	—	—	—	—	—	—	—	—	HV–A
—	—	—	—	—	—	—	—	—	—	HV–A
48.15	41.37	41.91	51.85	5.36	5.44	6.72	11,666	11,819	14,623	HV–A
42.38	48.95	49.59	57.62	1.24	1.25	1.45	12,659	12,824	14,900	HV–A
46.87	41.67	42.04	53.13	5.79	5.85	7.39	11,452	11,556	14,602	HV–A
44.71	43.50	43.92	55.29	4.38	4.42	5.56	11,624	11,737	14,774	HV–A
48.20	41.43	41.81	51.80	7.46	7.53	9.33	11,715	11,824	14,648	HV–A
45.96	46.45	47.05	54.04	5.09	5.16	5.92	12,775	12,940	14,862	HV–A
44.66	44.78	45.45	55.34	2.74	2.78	3.39	12,020	12,199	14,854	HV–A

Table 6.

County	Coal bed	Sample number	Total thickness of coal bed (feet)	Depth to base of coal bed (feet)	Total gas content of coal bed (cf/t)	Moisture (AR)[1]	Ash (AR)[1]	Ash (dry)	Volatile matter (AR)[1]	Volatile matter (dry)
Greene	Sewickley (top, 1.91 ft)[4]	D2–5a	[5]4.25	[5]938	[5]98	0.99	14.16	14.30	39.39	39.78
do.	Sewickley (bottom, 1.46 ft)[4]	D2–5b				.83	14.56	14.69	39.14	39.47
Somerset	Middle Kittanning	E1–1a—1b	6.85	108	28	—	—	—	—	—
do.	Lower Kittanning	E1–2a—2c	10.40	145	27	—	—	—	—	—
do.	Middle Kittanning (top, 3.33 ft)[4]	E2–1a	[5]6.00	[5]75	[5]29	1.13	12.44	12.58	17.19	17.39
do.	Middle Kittanning (bottom, 0.91 ft)[4]	E2–1b				1.37	12.33	12.50	15.72	15.93
do.	Lower Kittanning (top, 3.00 ft)[4]	E2–2a	[5]9.85	[5]108	[5]24	1.02	20.19	20.40	16.10	16.27
do.	Lower Kittanning (bottom, 3.08 ft)[4]	E2–2b				1.05	15.87	16.03	17.55	17.74
Westmoreland	Upper Freeport	F1	4.35	627	146	1.2	16.06	16.26	26.75	27.08
do.	do.	F2	4.23	708	175	1.0	10.67	10.78	27.45	27.73
do.	do.	F3	4.54	716	170	1.0	16.81	16.98	27.22	27.50
do.	do.	F4	3.51	639	164	1.1	12.03	12.16	28.47	28.79
do.	do.	F5	3.29	598	116	1.6	21.44	21.79	25.42	25.83
do.	do.	F6	4.19	646	177	1.0	17.82	18.00	28.19	28.47
do.	do.	F7	4.50	720	221	1.3	17.10	17.32	26.93	27.28
do.	do.	F8	4.35	607	275	1.3	17.84	18.07	27.39	27.75
do.	do.	F9	4.52	609	69	1.5	16.39	16.64	26.58	26.98

[1] AR, as received.

[2] daf, dry, ash-free.

[3] HV-A, high-volatile A bituminous coal; LV, low-volatile bituminous coal.

[4] Thickness of coal/canister represented in coal analyses.

[5] Value for entire coal bed.

(Continued)

Volatile matter (daf)[2]	Fixed carbon (AR)[1]	Fixed carbon (dry)	Fixed carbon (daf)[2]	Sulfur (AR)[1]	Sulfur (dry)	Sulfur (daf)[2]	Btu (AR)[1]	Btu (dry)	Btu (daf)[2]	Apparent rank[3]
46.42	45.46	45.92	53.58	3.33	3.36	3.92	12,744	12,871	15,018	HV-A
46.26	45.47	45.84	53.74	3.39	3.42	4.01	12,615	12,720	14,910	HV-A
—	—	—	—	—	—	—	—	—	—	LV
—	—	—	—	—	—	—	—	—	—	LV
19.89	69.24	70.03	80.11	2.98	3.01	3.45	13,369	13,521	15,468	LV
18.21	70.58	71.57	81.79	1.96	1.99	2.27	13,213	13,396	15,310	LV
20.44	62.69	63.33	79.56	2.06	2.08	2.61	11,972	12,095	15,195	LV
21.12	65.53	66.23	78.88	2.06	2.08	2.48	12,743	12,878	15,337	LV
—	55.99	56.66	—	2.09	2.12	—	12,731	12,886	15,387	HV-A
—	60.88	61.49	—	.95	.96	—	13,643	13,781	15,446	HV-A
—	54.97	55.52	—	2.51	2.53	—	12,678	12,806	15,426	HV-A
—	58.40	59.05	—	2.31	2.34	—	13,480	13,630	15,518	HV-A
—	51.54	52.38	—	2.13	2.16	—	11,803	11,995	15,337	HV-A
—	52.99	53.53	—	3.79	3.83	—	12,482	12,608	15,376	HV-A
—	54.67	55.40	—	2.69	2.71	—	12,591	12,757	15,429	HV-A
—	53.47	54.18	—	2.81	2.84	—	12,401	12,564	15,336	HV-A
—	55.53	56.38	—	1.57	1.59	—	12,646	12,838	15,401	HV-A

APPENDIX 2

COMPOSITION AND HEATING

Appendix 2 consists of three tables (Tables 7, 8, and 9) that show the composition and heating values of Somerset Counties. Table 8 shows the composition and heating values from a gob gas ventilation borehole in hole in Greene County.

Table 7. *Composition and Heating Values of Coal-Bed*

County	Coal bed	Sample number	Date sampled	Methane (CH_4)	Ethane (C_2H_6)	Propane (C_3H_8)	1-butene (C_4H_8)	Isobutane ($i\text{-}C_4H_{10}$)
Armstrong	Upper Kittanning	A1–1	7–25–88	98.40	0.0438	0.0007	0	0.0007
do.	Lower Kittanning	A1–2a (top)	7–25–88	93.75	.0642	.0017	0	.0017
do.	do.	A1–2b (middle)	7–25–88	98.17	.0479	.0003	0	.0003
do.	do.	A1–2c (bottom)	7–25–88	96.73	.0572	.0006	0	0
do.	Upper Kittanning	A2–1	7–25–88	46.87	.0879	0	0	.0330
do.	Lower Kittanning	A2–2a (top)	7–25–88	72.53	.0769	0	0	0
do.	do.	A2–2b (bottom)	7–25–88	83.80	.0546	.0018	0	.0053
Cambria	Upper Freeport (top)	B1–1a	12–18–88	98.90	.0413	.0005	.0003	0
do.	Upper Freeport (middle)	B1–1b	12–18–88	99.85	.0186	.0001	.0001	0
do.	Upper Freeport (shaly coal)	B1–1c	12–18–88	97.83	.0068	.0002	.0002	0
do.	Lower Freeport (top)	B1–2a	12–18–88	99.81	.0142	.0002	.0001	0
do.	Lower Freeport (top) (residual gas)	B1–2a	8–23–89	88.27	.0752	.0011	.0011	0
do.	Lower Freeport (bottom)	B1–2b	12–18–88	99.55	.0186	.0004	.0003	0
Greene	Ten Mile Coal	D2–1	9–1–88	96.61	1.9166	.0008	0	.0239
do.	do.	D2–1	9–14–88	92.86	1.5818	.0011	0	.0201
do.	do.	D2–1	12–21–88	95.38	1.5003	.0012	.0156	0
do.	do.	D2–1	3–8–89	93.68	1.7449	.0009	.0149	0
do.	Ten Mile Coal (residual gas)	D2–1	8–23–89	77.34	3.4479	.0032	.0548	0
do.	Little Washington	D2–2	9–1–88	97.34	1.2973	.0015	0	.0187
do.	do.	D2–2	9–14–88	97.10	1.2279	.0017	0	.0193
do.	do.	D2–2	12–8–88	94.35	1.6003	.0032	.0226	0
do.	do.	D2–2	3–7–89	88.93	2.8820	.0037	.0201	0
do.	Little Washington (residual gas)	D2–2	8–23–89	85.23	3.3980	.0034	.0661	0
do.	Waynesburg A (top)	D2–3a	9–1–88	94.30	1.2754	0	0	.0299
do.	do.	D2–3a	9–14–88	94.34	.8944	.0001	0	.0252
do.	do.	D2–3a	12–8–88	89.09	1.0016	.0103	.0319	0
do.	do.	D2–3a	3–7–89	72.48	1.8349	.0018	.0321	0
do.	Waynesburg A (top) (residual gas)	D2–3a	8–23–89	82.72	4.2189	.0018	.1468	0
do.	Waynesburg A (bottom)	D2–3b	9–1–88	93.32	1.4140	.0201	0	.0796
do.	do.	D2–3b	9–14–88	93.33	1.3376	.0200	0	.0791
do.	do.	D2–3b	3–8–89	56.55	1.8158	.0143	.0350	0
do.	Waynesburg (top)	D2–4a	9–1–88	96.21	.1967	.0021	0	.0044
do.	do.	D2–4a	9–14–88	95.96	.3029	.0021	0	.0038
do.	do.	D2–4a	12–21–88	82.44	.3722	.0059	.0049	0
do.	do.	D2–4a	3–8–89	8.08	.0790	.0016	.0013	0
do.	Waynesburg (middle)	D2–4b	9–1–88	95.93	.0492	0	0	.0125
do.	do.	D2–4b	9–14–88	95.81	.0577	0	0	.0132
do.	do.	D2–4b	12–24–88	93.60	.0946	.0005	.0106	0
do.	do.	D2–4b	3–8–89	87.16	.0942	.0010	.0127	0
do.	Waynesburg (middle) (residual gas)	D2–4b	8–24–89	88.88	.1127	.0010	.0749	0
do.	Waynesburg (bottom)	D2–4c	9–1–88	96.09	.0202	0	0	.0054
do.	do.	D2–4c	9–14–88	95.64	.0202	0	0	.0046

VALUES OF COAL-BED METHANE

coal-bed methane in Pennsylvania. Table 7 shows the values from coals in Armstrong, Cambria, Greene, and Greene County; Table 9 contains similar information obtained from methane in the Waynesburg College core

Methane for Armstrong, Cambria, Greene, and Somerset Counties[1]

n-butane ($n\text{-}C_4H_{10}$)	Isopentane ($i\text{-}C_5H_{12}$)	n-pentane ($n\text{-}C_5H_{12}$)	Ethylene (C_2H_4)	Propylene (C_3H_6)	H_2	CO_2	N_2	CO	Heating value Btu/scf	Heating value Btu/mcf
0	0.0007	0	0	0	0	0.47	1.04	0.06	1,061	1.06
.0017	0	0	0	0	0	1.91	4.17	.06	1,012	1.01
.0003	0	0	0	0	0	.63	1.10	.03	1,058	1.06
.0006	0	0	0	0	0	.88	2.28	.03	1,043	1.04
.0165	.0385	0	0	0	0	8.24	43.96	.21	509	.51
0	0	0	0	0	0	5.00	21.98	.14	783	.78
.0035	.0018	0	0	0	0	1.43	14.44	.05	905	.91
.0002	0	0	.0003	.0005	.19	.19	.67	.0042	1,066	1.07
.0001	0	0	.0001	.0003	.09	.11	0	.0025	1,076	1.08
.0002	0	0	.0005	.0002	.39	.22	1.54	.01	1,056	1.06
.0001	0	0	0	.0002	.07	.08	.03	.0020	1,076	1.08
.0008	0	0	.0011	.0015	.50	.30	3.23	.03	954	.95
.0003	0	0	.0003	.0005	.16	.13	.13	.01	1,073	1.07
.0118	.0236	.0058	0	0	0	.95	.43	.04	1,078	1.08
.0062	.0158	.0034	0	0	.04	4.88	.50	.03	1,031	1.03
.0032	0	0	.0017	.0017	.40	.26	2.39	.02	1,057	1.06
.0032	0	0	.0020	.0014	.46	3.29	.77	.02	1,044	1.04
.0032	0	0	.0054	.0054	1.48	6.66	5.69	.13	904	.90
.0030	.0122	.0022	0	0	0	1.24	.08	.0016	1,073	1.07
.0025	.0116	.0024	0	0	0	1.45	.16	.0012	1,070	1.07
.0020	0	0	0	.0014	.30	2.38	1.35	.01	1,047	1.05
.0023	0	0	.0018	.0018	.37	4.94	2.88	.02	1,014	1.01
.0023	0	0	0	.0023	.91	3.25	6.33	.08	986	.99
.0034	.0203	.0039	0	0	0	3.66	.70	.0034	1,041	1.04
.0027	.0156	.0029	0	0	0	4.17	.51	.0013	1,034	1.03
.0037	0	0	.0011	.0013	.55	7.20	1.29	.02	980	.98
.0046	0	0	.0028	.0037	.73	13.49	11.28	.04	819	.82
.0053	0	0	.0036	.0024	.84	5.09	4.08	.08	974	.97
.0265	.0480	.0113	0	0	0	4.40	.66	.0080	1,036	1.04
.0242	.0460	.0126	0	0	0	4.73	.38	.0341	1,035	1.04
.0169	0	0	.0065	.0013	2.59	22.83	15.95	.2036	654	.65
.0026	.0061	.0004	0	0	0	2.94	.62	.0033	1,040	1.04
.0019	.0055	.0005	0	0	0	3.39	.31	.0017	1,039	1.04
.0027	0	0	.0011	.0022	1.13	10.64	5.35	.0627	899	.90
.0011	0	0	.0013	.0013	.39	5.93	85.47	.04	90	.09
.0030	.0089	.0007	0	0	0	3.36	.54	.01	1,035	1.04
.0013	.0085	.0009	0	0	0	3.72	.27	.0011	1,034	1.03
.0009	0	0	.0007	.0011	0	5.25	.63	.02	1,010	1.01
.0013	0	0	.0010	.0013	.48	9.23	3.01	.02	943	.94
.0015	0	0	.0015	.0020	.73	4.47	3.87	.07	962	.96
.0006	.0030	.0001	0	0	0	3.18	.64	.0050	1,036	1.04
.0002	.0022	.0001	0	0	0	4.07	.22	.0012	1,030	1.03

Table 7.

County	Coal bed	Sample number	Date sampled	Methane (CH_4)	Ethane (C_2H_6)	Propane (C_3H_8)	1-butene (C_4H_8)	Isobutane ($i\text{-}C_4H_{10}$)
Greene	Waynesburg (bottom)	D2–4c	12– 8–88	94.57	0.0884	0.0004	0.0104	0
do.	do.	D2–4c	8–21–89	91.42	.0212	.0004	.0029	0
do.	Waynesburg (bottom) (residual gas)	D2–4c	8–24–89	85.80	.0804	.0010	.0146	0
do.	Sewickley (top)	D2–5a	9– 1–88	89.69	1.3271	.0008	0	.0036
do.	do.	D2–5a	9–14–88	91.65	1.5032	.0012	0	.0168
do.	do.	D2–5a	12–21–88	86.74	2.0477	.0004	.0143	0
do.	do.	D2–5a	8–21–89	87.39	2.2032	.0016	.0060	0
do.	Sewickley (top) (residual gas)	D2–5a	8–24–89	80.16	5.8773	.0086	.0545	0
do.	Sewickley (bottom)	D2–5b	9– 1–88	92.37	1.0099	.0003	0	.0054
do.	do.	D2–5b	9–14–88	89.94	1.6528	.0012	0	.0124
do.	do.	D2–5b	12– 8–88	88.83	.0710	.0005	.0062	0
do.	do.	D2–5b	3– 8–89	63.75	2.6564	.0043	.0103	0
do.	Sewickley (bottom) (residual gas)	D2–5b	8–24–89	83.55	5.6297	.0040	.0841	0
Somerset	Middle Kittanning (top)	E1–1a	12– 4–88	3.75	.0004	.0004	.0006	0
do.	do.	E1–1a	3–14–89	1.21	.0019	.0001	.0001	0
do.	Middle Kittanning (bottom)	E1–1b	12– 4–88	1.25	.0325	.0003	.0005	0
do.	do.	E1–1b	3– 9–89	.11	.0016	.0003	.0002	0
do.	Lower Kittanning (top)	E1–2a	12– 4–88	.10	.0020	0	.0003	0
do.	do.	E1–2a	3–14–89	.12	.0008	.0001	.0001	0
do.	Lower Kittanning (top) (residual gas)	E1–2a	8–17–89	2.44	.0439	.0098	.0098	0
do.	Lower Kittanning (middle)	E1–2b	12– 4–88	.08	.0010	.0003	.0003	0
do.	do.	E1–2b	3–14–89	.07	.0009	.0001	.0001	0
do.	Lower Kittanning (bottom)	E1–2c	11–29–88	.27	.0014	.0004	.0004	0
do.	do.	E1–2c	3– 7–89	.11	.0014	.0003	.0001	0
do.	Middle Kittanning (top)	E2–1a	11–29–88	.40	.0011	.0004	.0002	0
do.	do.	E2–1a	3– 9–89	.05	.0009	.0003	.0001	0
do.	Middle Kittanning (bottom)	E2–1b	12– 4–88	.04	.0013	.0003	.0003	0
do.	do.	E2–1b	3– 9–89	.08	.0011	.0002	.0002	0
do.	Lower Kittanning (top)	E2–2a	11–29–88	.09	.0013	.0004	.0004	0
do.	do.	E2–2a	3– 9–89	.09	.0009	.0003	.0001	0
do.	Lower Kittanning (bottom)	E2–2b	11–29–88	.10	.0016	.0004	.0004	0
do.	do.	E2–2b	3–14–89	.05	.0010	.0003	.0003	0

[1] Data in normalized percent.

(Continued)

n-butane ($n\text{-}C_4H_{10}$)	Isopentane ($i\text{-}C_5H_{12}$)	n-pentane ($n\text{-}C_5H_{12}$)	Ethylene (C_2H_4)	Propylene (C_3H_6)	H_2	CO_2	N_2	CO	Heating value	
									Btu/scf	Btu/mcf
0.0009	0	0	0.0004	0.0006	0.22	3.56	1.53	0.01	1,022	1.02
.0004	0	0	.0006	.0008	.22	6.73	1.22	.01	986	.99
.0010	0	0	.0010	.0016	.72	5.12	6.06	.10	928	.93
.0006	.0016	.0003	0	0	0	7.29	1.67	0	991	.99
.0023	.0093	.0013	0	0	0	7.10	0	.0013	1,016	1.02
.0021	0	0	.0005	.0007	.28	10.06	.85	.01	974	.97
.0008	0	0	0	.0010	.20	10.57	.37	.01	983	.98
.0029	0	0	0	.0017	.46	6.14	3.38	.05	976	.98
.0012	.0028	.0002	0	0	0	6.05	.56	.0015	1,014	1.01
.0012	.0076	.0010	0	0	0	8.08	.30	.0011	1,001	1.00
.0009	0	0	.0006	2.0882	.24	7.94	.80	.0082	959	.96
.0009	0	0	.0026	.0043	1.20	25.02	7.28	.1003	742	.74
.0035	0	0	0	.0020	.59	5.18	5.33	.0637	1,009	1.01
.0003	0	0	0	.1061	.11	4.63	91.40	.01	40	.04
.0001	0	0	.0004	.0003	.23	4.51	94.05	.0097	14	.01
.0003	0	0	.0006	.0008	.17	4.07	94.47	.01	14	.01
.0002	0	0	.0004	.0004	.24	3.18	96.45	.01	2	.002
.0003	0	0	.0004	.0003	.09	3.15	96.65	.01	1	.001
.0001	0	0	.0003	.0003	.20	3.64	96.03	.01	2	.002
.0098	0	0	.0146	.0146	9.04	50.73	30.24	.55	61	.06
.0003	0	0	.0004	.0006	.04	2.61	97.27	.01	1	.001
.0001	0	0	.0003	.0003	.23	3.67	96.03	.01	2	.002
.0002	0	0	.0008	.0010	.25	3.42	96.03	.03	4	.004
.0003	0	0	.0004	.0006	.20	3.05	96.63	.01	2	.002
.0002	0	0	.0005	.0007	.40	2.79	96.38	.02	5	.01
.0001	0	0	.0003	.0004	.20	2.53	97.20	.01	2	.002
.0003	0	0	.0004	.0006	.01	1.52	98.39	.02	1	.001
.0002	0	0	.0004	.0004	.28	2.84	96.71	.07	2	.002
.0004	0	0	.0006	.0008	.15	1.66	98.08	.01	2	.002
.0003	0	0	.0004	.0004	.21	1.60	98.06	.01	2	.002
.0004	0	0	.0006	.0010	.06	1.33	98.49	.01	1	.001
.0002	0	0	.0004	.0004	.22	1.65	98.08	.01	2	.002

Table 8. *Composition and Heating Values of Coal-Bed Methane From a Gob Gas Ventilation Borehole in Greene County*[1]

	Methane (CH_4)	Hexane (C_6H_{14})	Pentane (C_5H_{12})	Butane (C_4H_{10})	Propane (C_3H_8)	Propylene (C_3H_6)	Ethane (C_2H_6)	CO_2	Ar	O_2	H_2O	N_2	Heating value	
													Btu/scf	Btu/mcf
1st run	90.7	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.1	1.4	0.6	6.2	1,077	1.08
2nd run	57.7	.0	.0	.0	.0	.0	.0	.7	.3	8.5	.0	32.8	937	.94
3rd run	95.5	.0	.0	.3	.4	.0	.6	.8	.0	.0	.0	2.3	1,062	1.06
4th run	92.7	.0	.5	.2	.7	.0	1.3	.8	.0	.0	.2	3.5	1,070	1.07
5th run	95.4	.1	.2	.2	.5	.0	.9	1.8	.0	.0	.0	1	1,073	1.07
6th run	94.1	.0	.0	.3	.2	.1	.3	4.1	.0	.0	.0	.8	1,034	1.03
7th run	94.3	.0	.0	.2	.2	.0	.3	4	.0	.0	.0	.9	1,034	1.03
8th run	92.7	.0	.0	.2	.3	.0	.4	3.3	.0	.8	.0	2.2	1,029	1.03

[1] Analysis took place over a 4-month period; raw data in percent.

Table 9. *Composition and Heating Values of Coal-Bed Methane From the Waynesburg College Core Hole, Franklin Township, Greene County*[1]

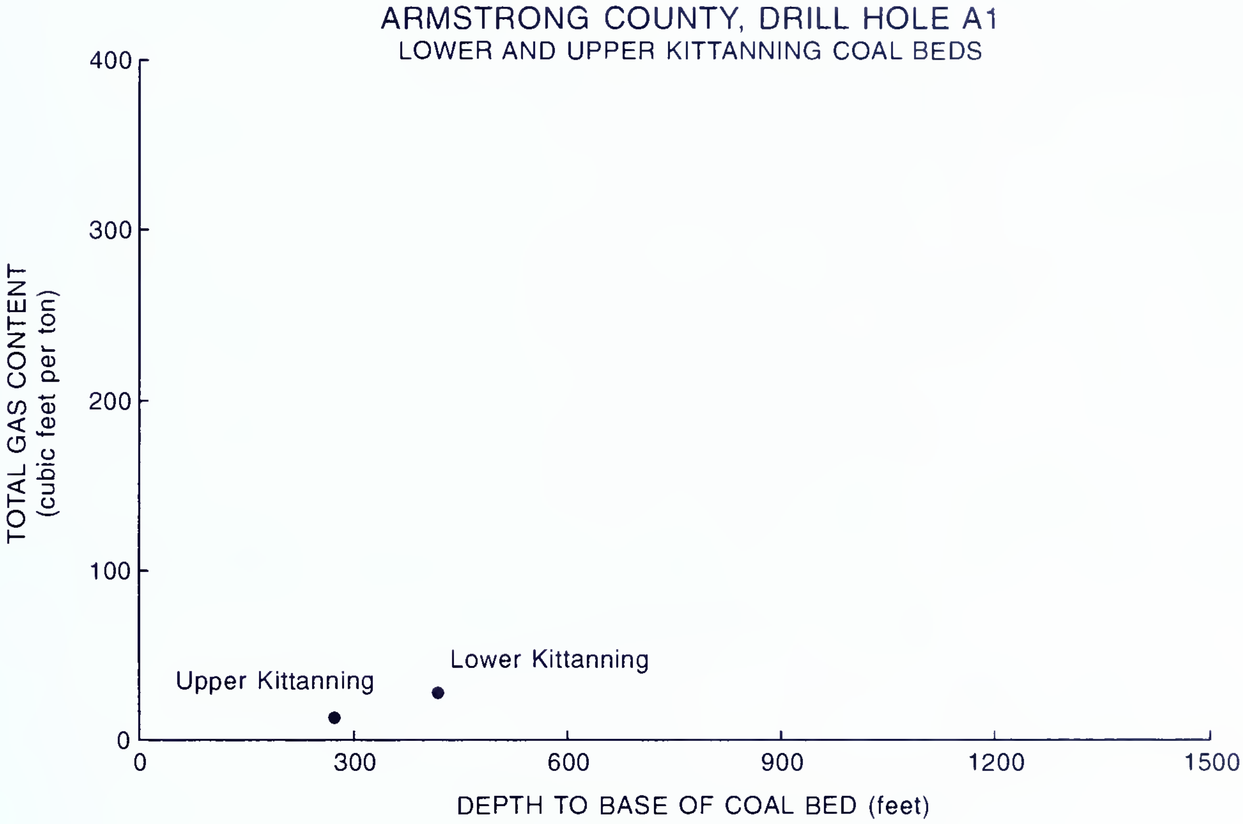
Sample number and coal bed	Methane (CH_4)	Ethane (C_2H_6)	Propane (C_3H_8)	H_2	CO_2	N_2	O_2	Heating value	
								Btu/scf	Btu/mcf
Sample 1 Waynesburg	45.50	0.02	—	—	2.49	51.20	0.81	494	0.49
Sample 2 Waynesburg	44.72	.02	—	0.02	2.33	52.07	.84	493	.49
Sample 3 Sewickley	58.69	.03	—	—	3.10	37.99	2.98	652	.65
Sample 4 Pittsburgh	51.57	1.02	—	—	9.02	37.74	.65	578	.58
Sample 5 Pittsburgh	59.86	1.25	—	—	8.00	30.08	.79	674	.67
Sample 6 Pittsburgh	54.35	1.01	—	1.22	7.17	35.45	.79	613	.61
Sample 7 Pittsburgh rider	74.10	1.23	—	.75	6.14	17.44	.34	827	.83
Sample 8 Bakerstown	75.77	1.88	0.17	.41	.73	20.62	.43	862	.86
Sample 9 Upper Freeport	41.76	1.00	.16	.54	.37	54.51	1.66	482	.48
Sample 10 Upper Kittanning	34.60	.99	.19	—	.76	55.90	7.60	429	.43
Sample 11 Upper Kittanning	16.52	.31	.07	—	6.21	74.55	2.35	190	.19
Sample 12 Middle Kittanning	58.38	2.62	.48	—	.68	35.26	2.57	709	.71
Sample 13 Clarion	87.15	2.18	.29	—	1.00	9.12	.26	990	.99

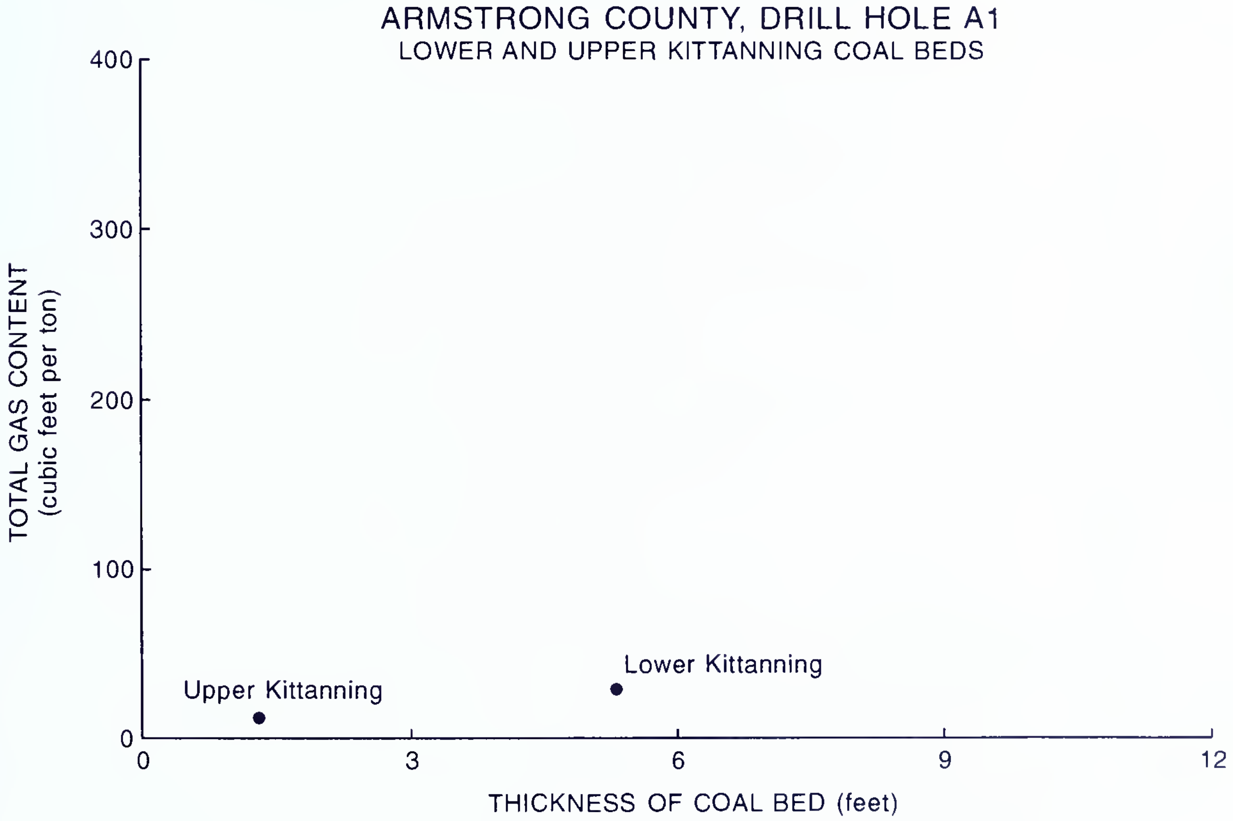
[1] From TRW Energy Systems Group (1980); raw data in percent.

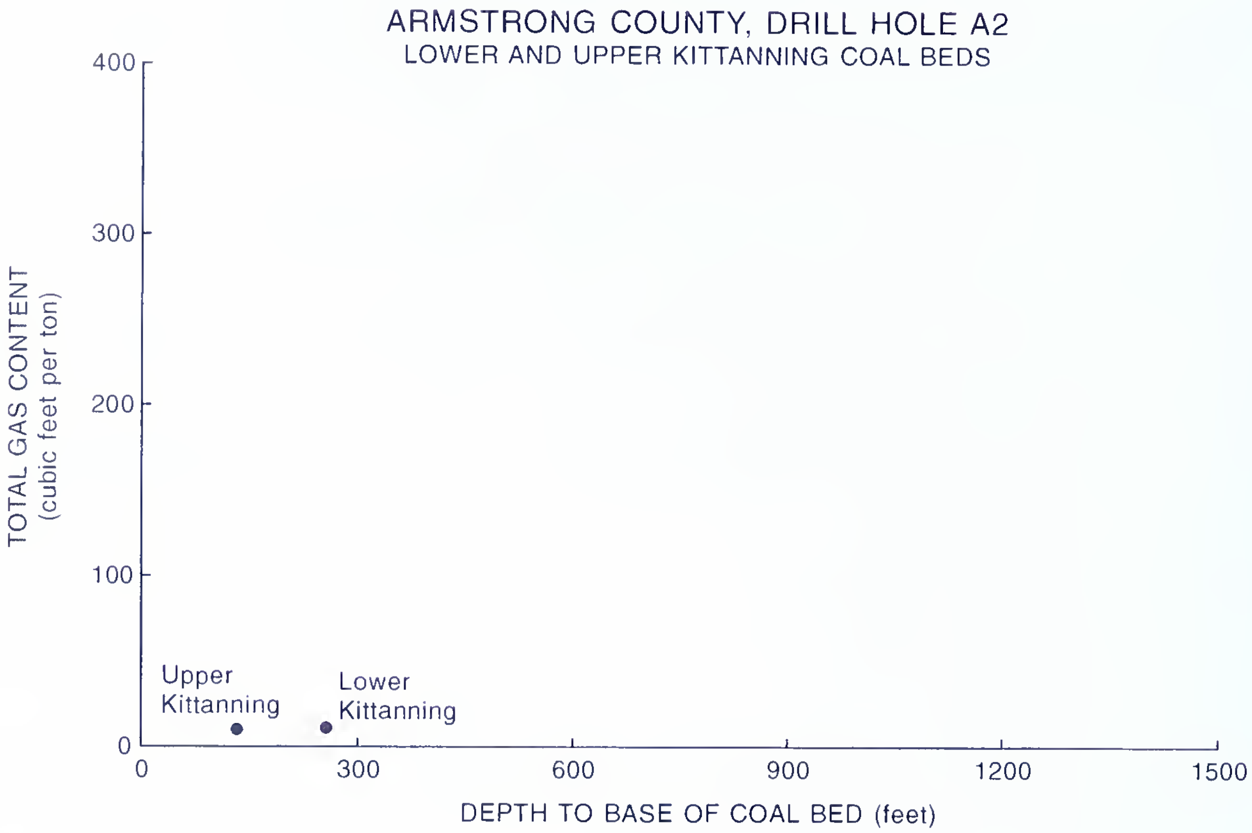
APPENDIX 3

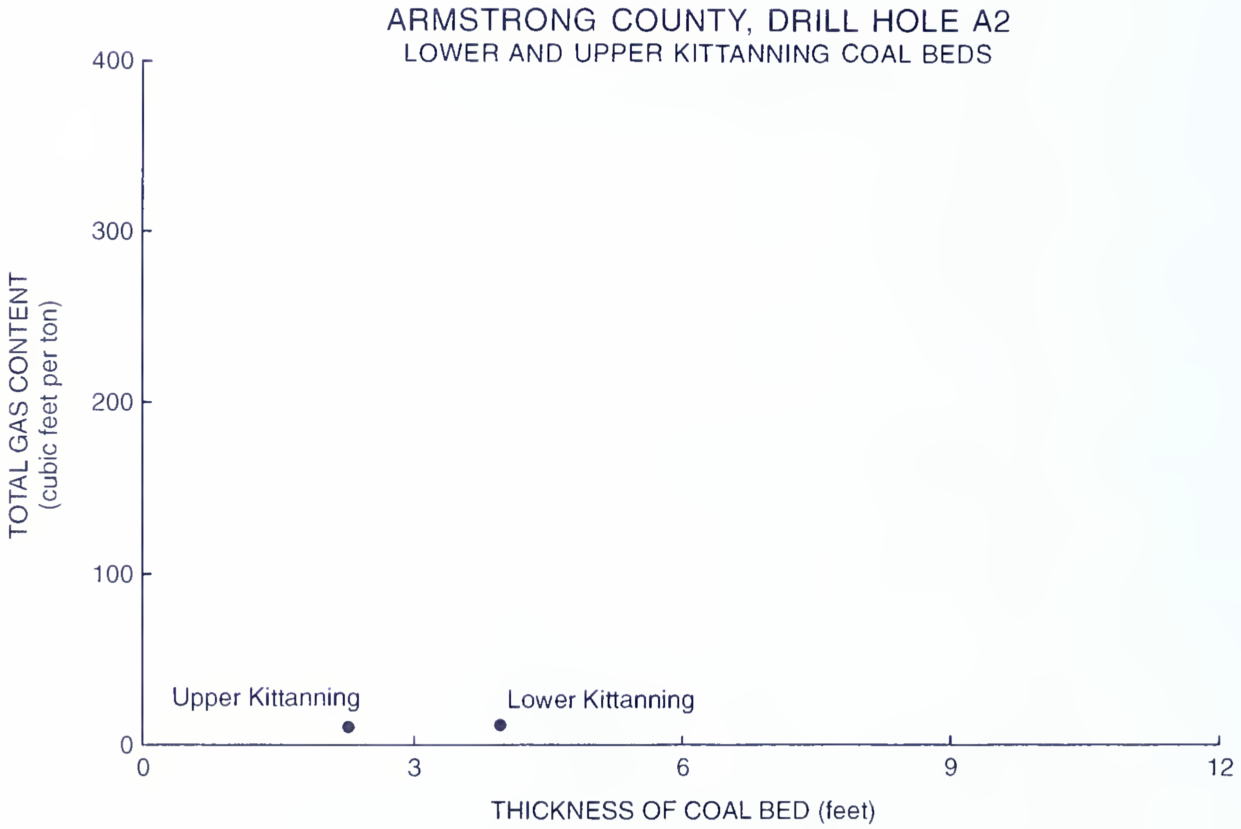
GAS CONTENT AND CUMULATIVE-GAS CONTENT

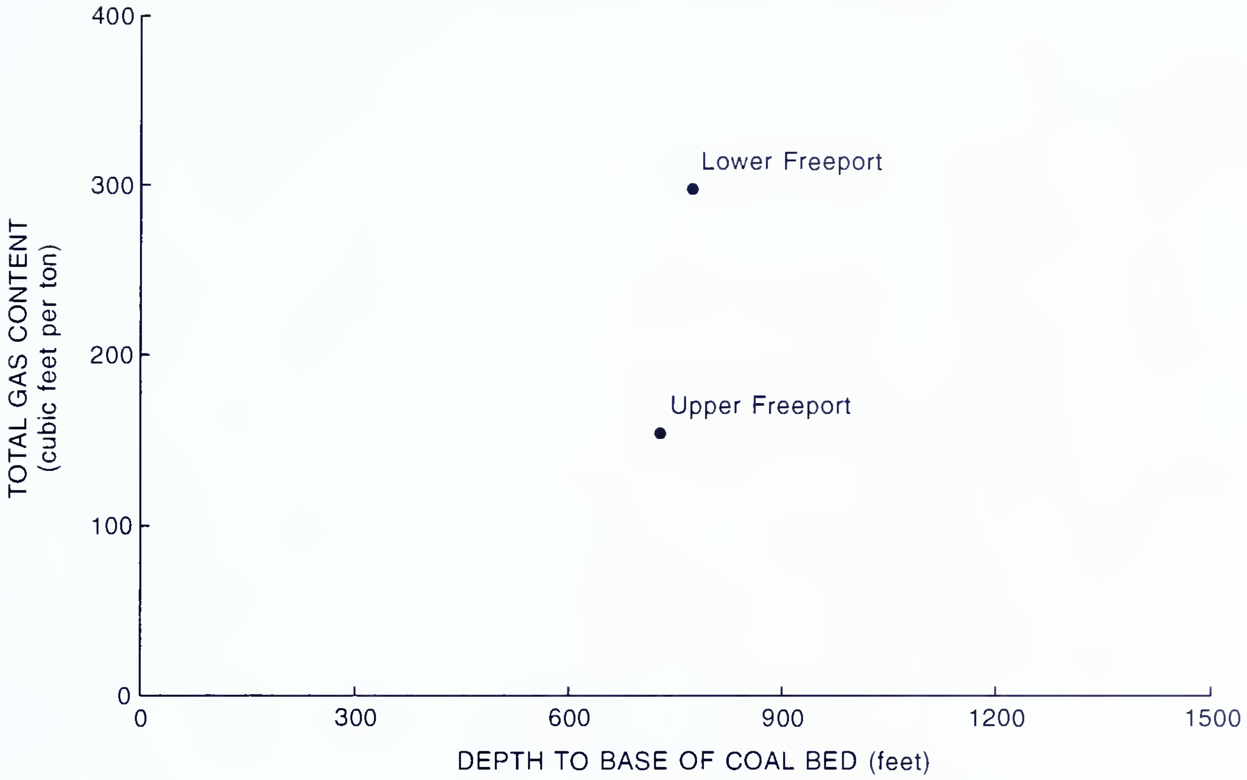
The following graphs show depth to the base of the coal bed versus total gas content and thickness of the coal bed versus total gas content for the coal beds considered in this study in Armstrong, Cambria, Fayette, Greene, Somerset, and Westmoreland Counties.



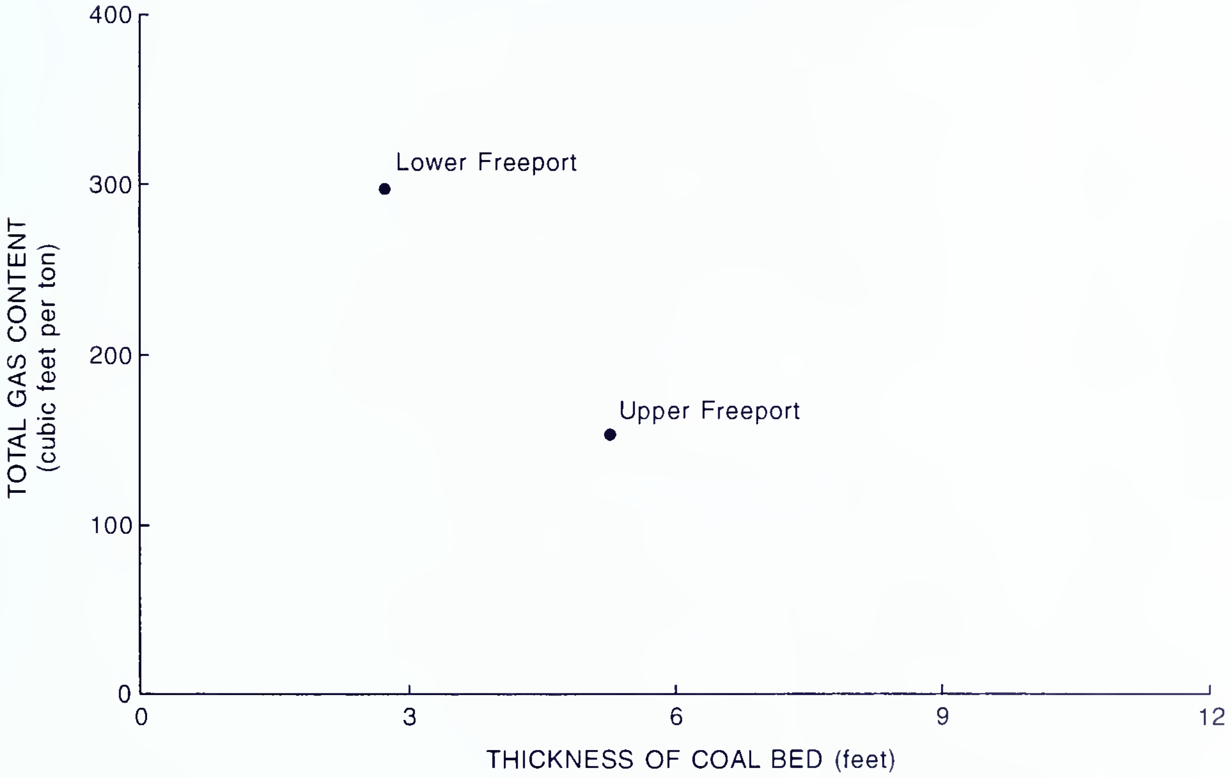



ARMSTRONG COUNTY, DRILL HOLE A2
LOWER AND UPPER KITTANNING COAL BEDS
TOTAL GAS CONTENT (cubic feet per ton)
400
300
200
100
0
Upper Kittanning
Lower Kittanning
0
300
600
900
1200
1500
DEPTH TO BASE OF COAL BED (feet)

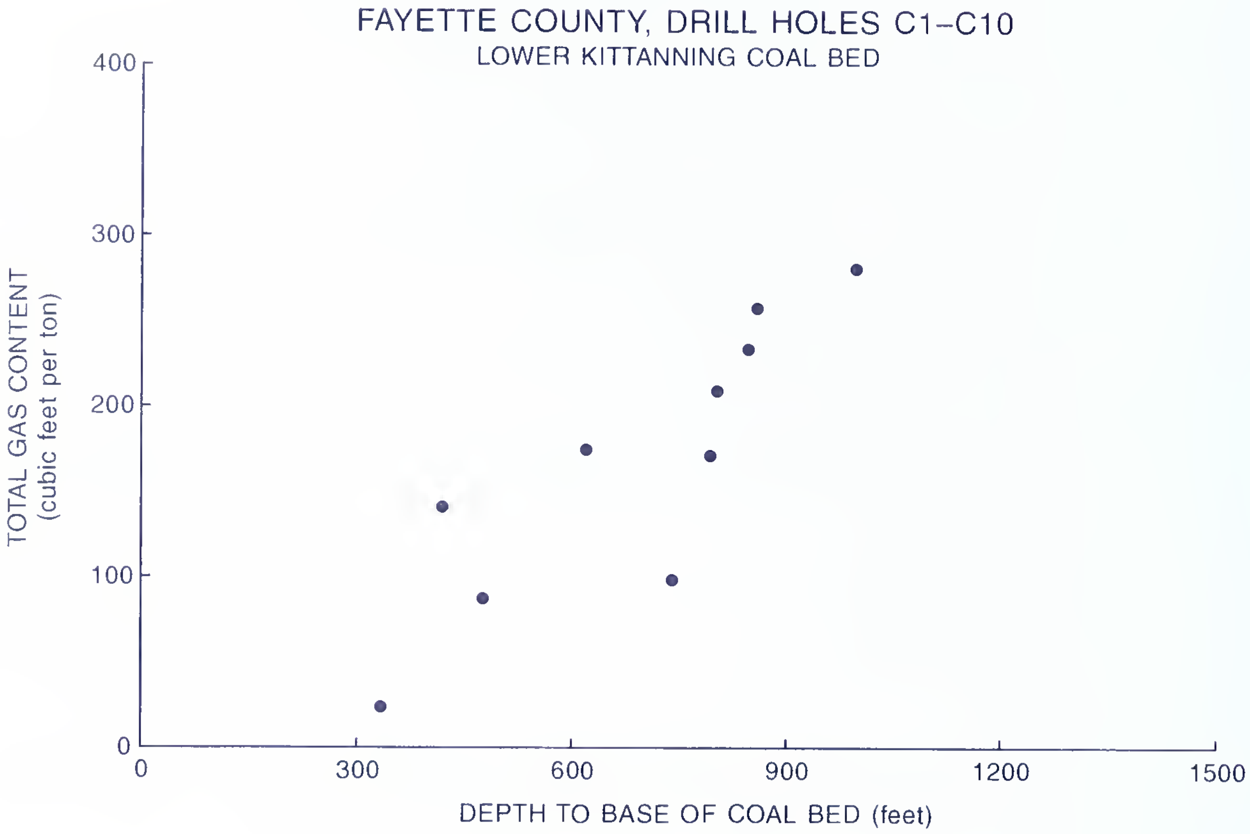

ARMSTRONG COUNTY, DRILL HOLE A2
LOWER AND UPPER KITTANNING COAL BEDS
TOTAL GAS CONTENT (cubic feet per ton)
400
300
200
100
0
Upper Kittanning
Lower Kittanning
0
3
6
9
12
THICKNESS OF COAL BED (feet)

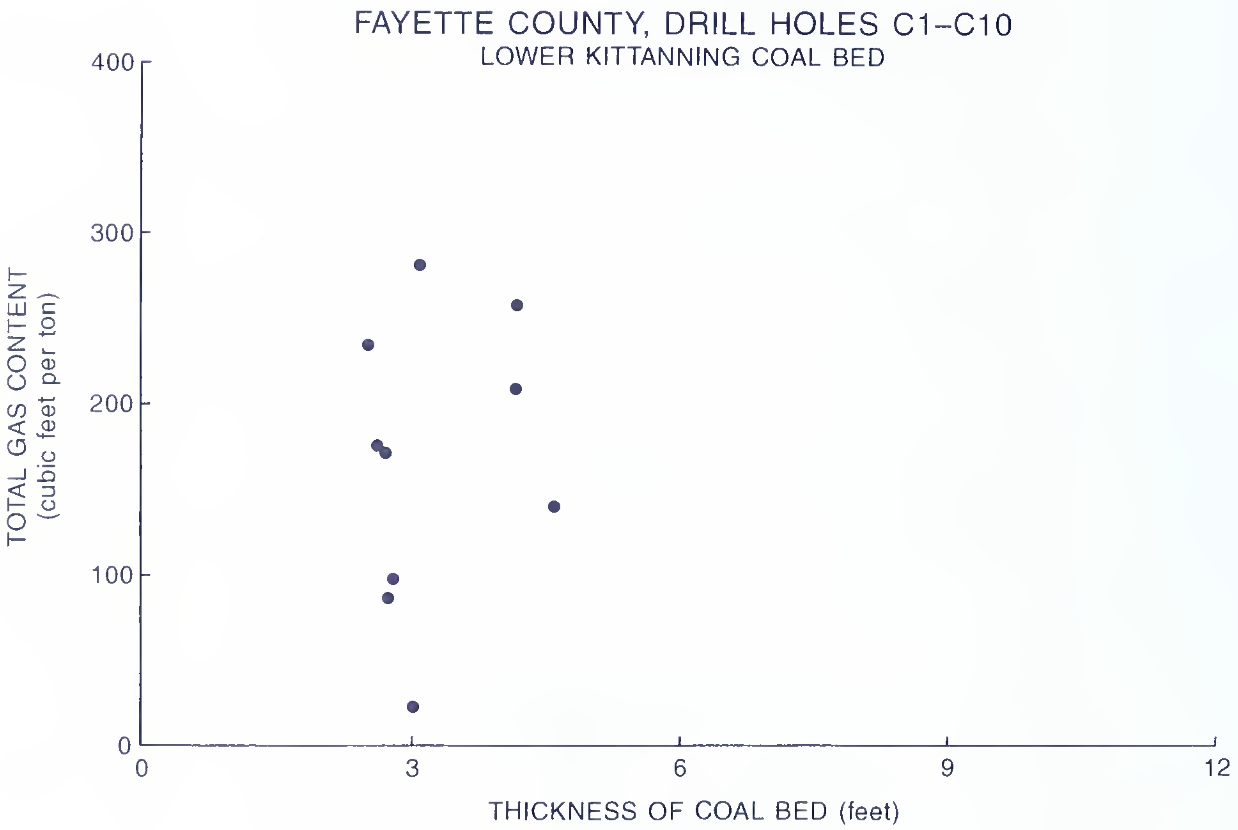


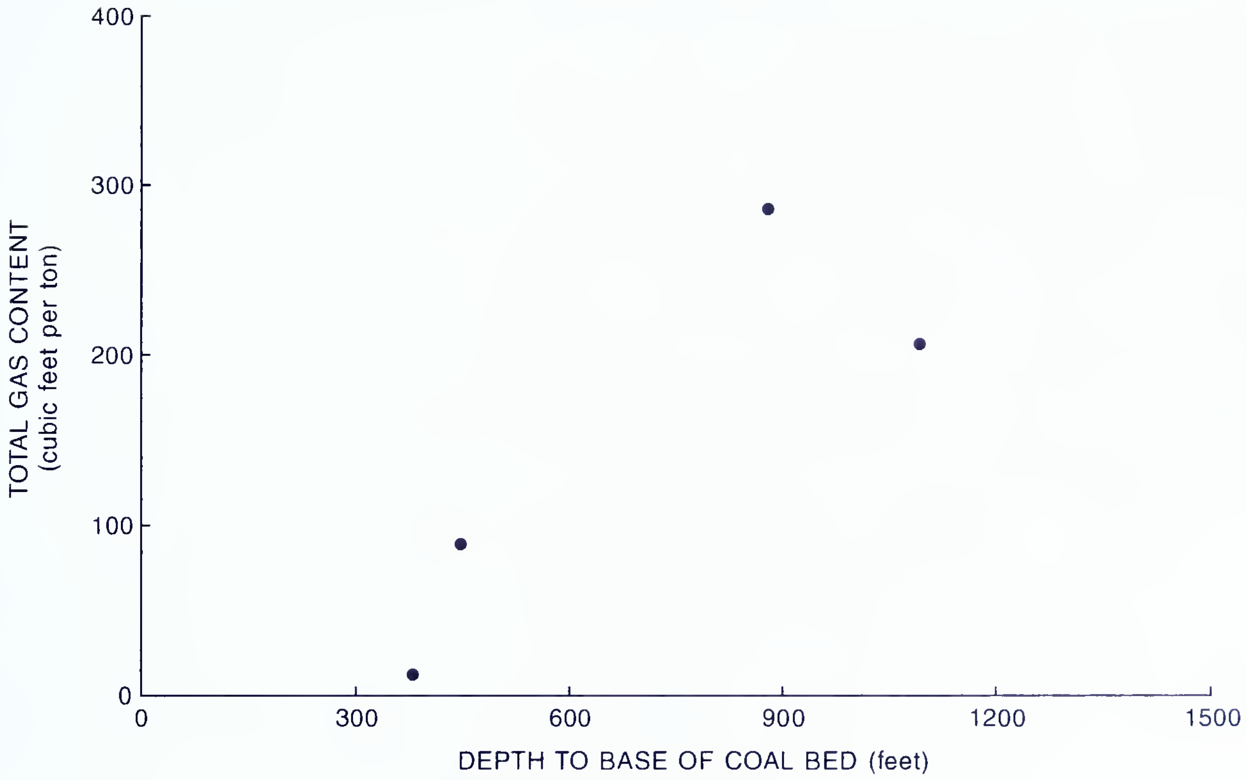
CAMBRIA COUNTY, DRILL HOLE B1
LOWER AND UPPER FREEPORT COAL BEDS



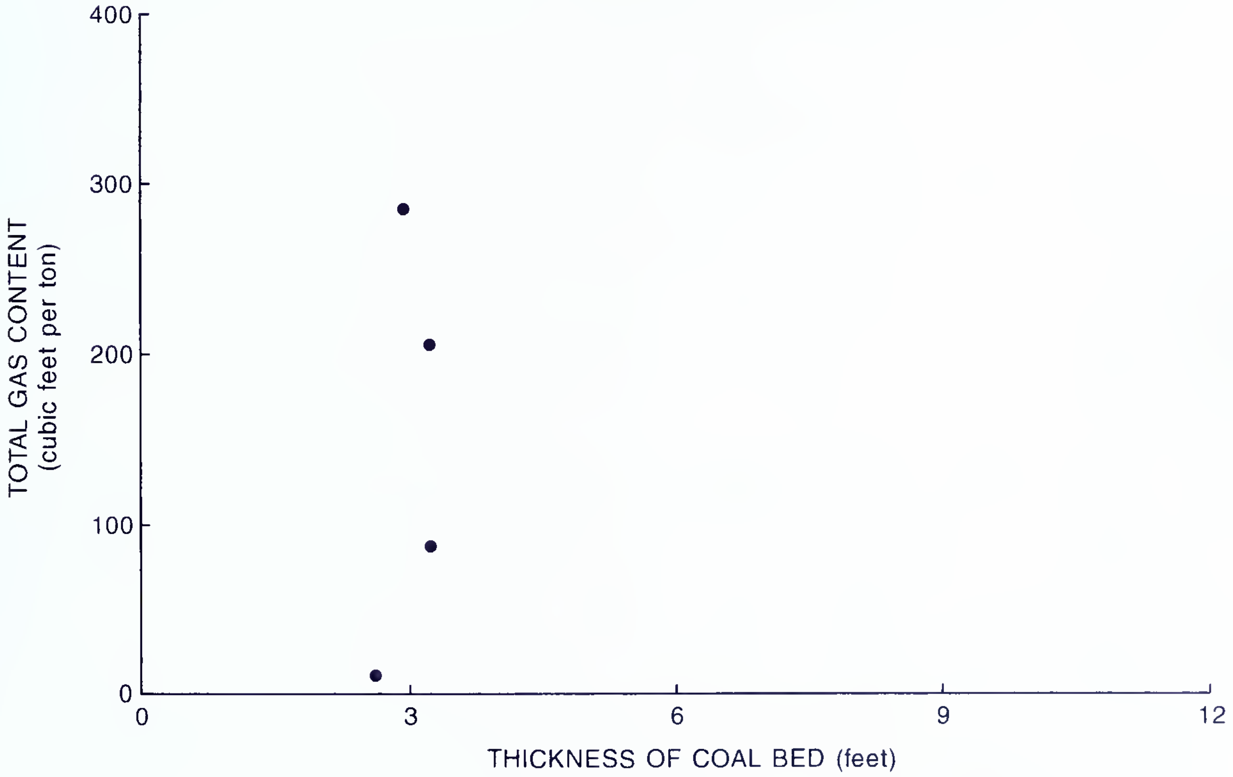
CAMBRIA COUNTY, DRILL HOLE B1
LOWER AND UPPER FREEPORT COAL BEDS


FAYETTE COUNTY, DRILL HOLES C1–C10
LOWER KITTANNING COAL BED
TOTAL GAS CONTENT (cubic feet per ton)
400
300
200
100
0
0
300
600
900
1200
1500
DEPTH TO BASE OF COAL BED (feet)

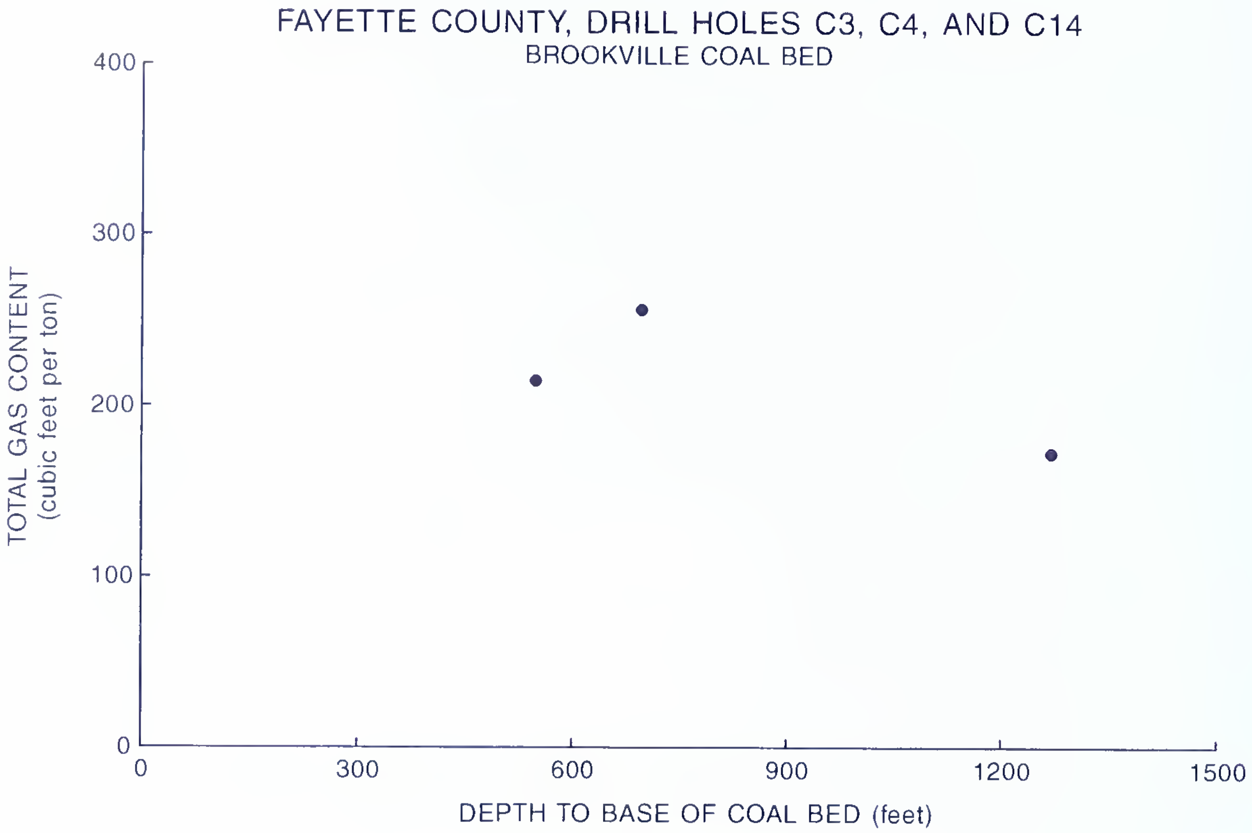

FAYETTE COUNTY, DRILL HOLES C1–C10
LOWER KITTANNING COAL BED
TOTAL GAS CONTENT (cubic feet per ton)
400
300
200
100
0
0
3
6
9
12
THICKNESS OF COAL BED (feet)

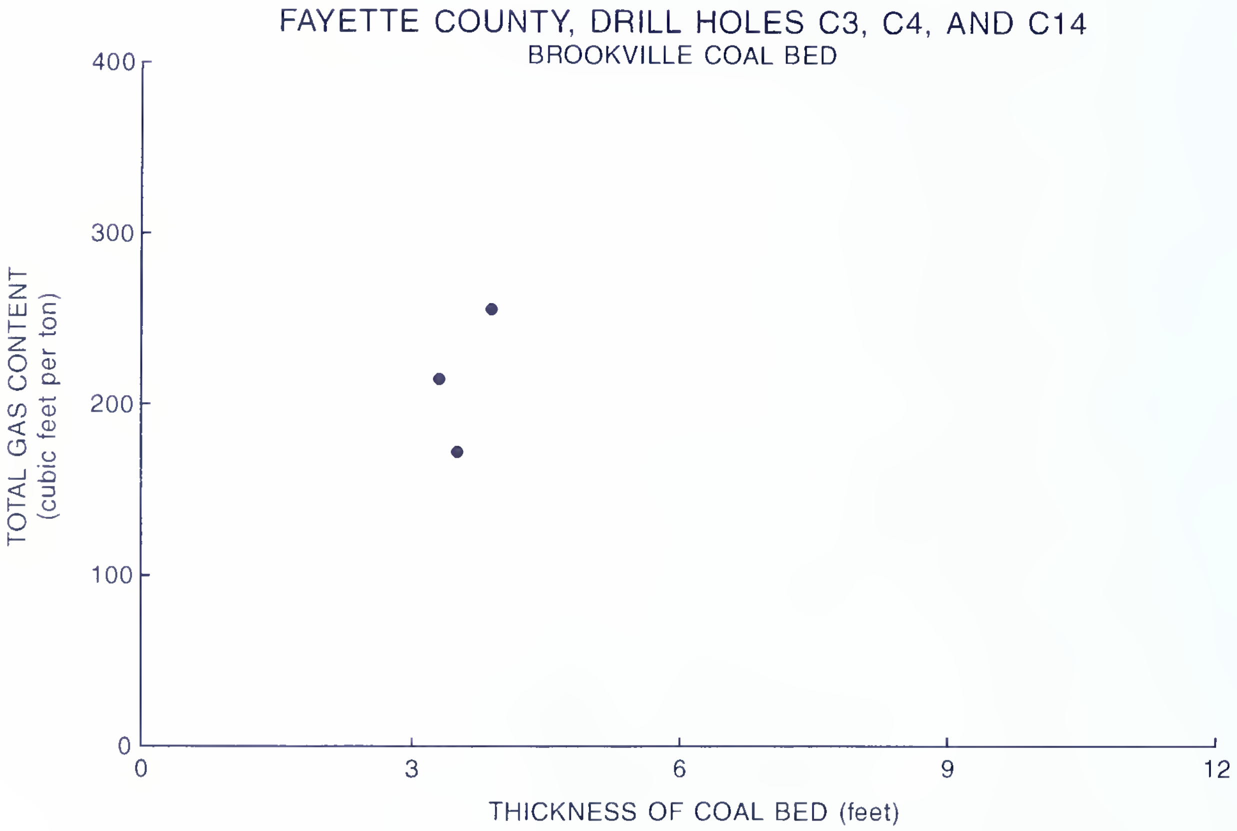


FAYETTE COUNTY, DRILL HOLES C8, C11, C12, AND C13
CLARION COAL BED

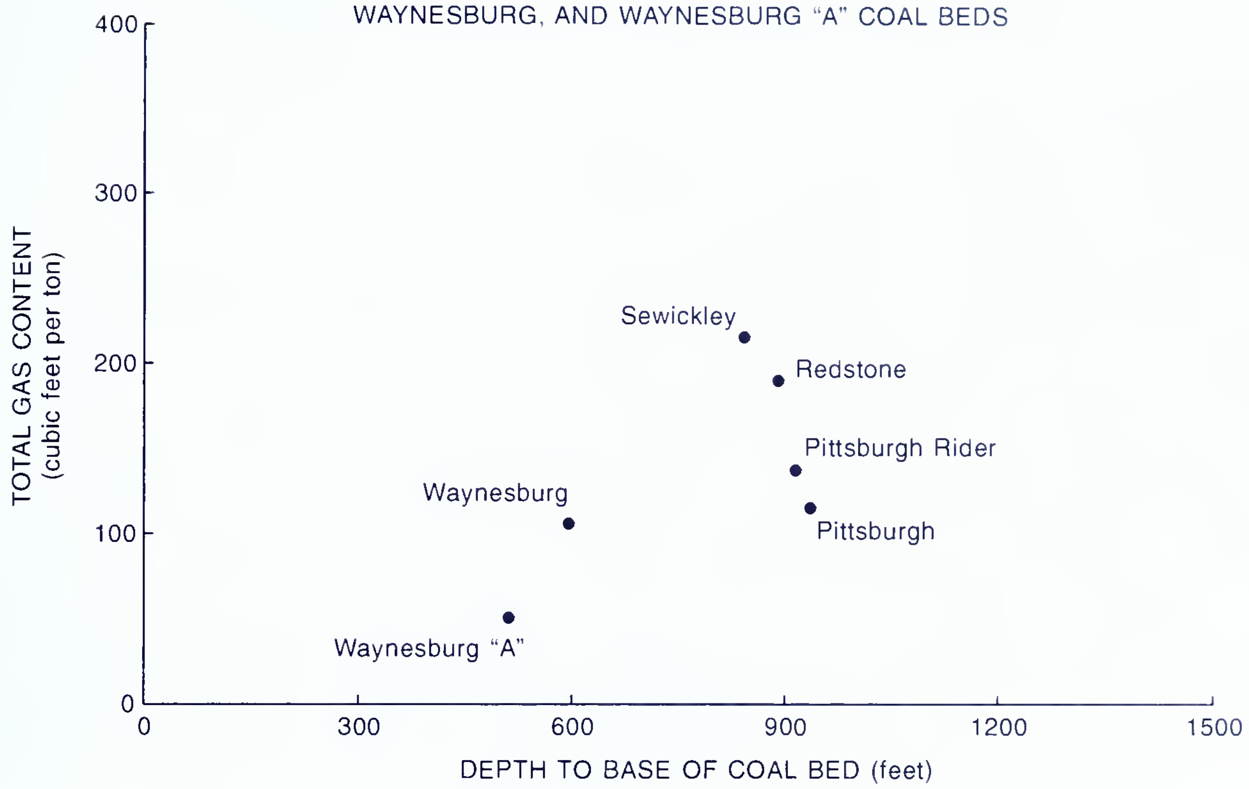


FAYETTE COUNTY, DRILL HOLES C8, C11, C12, AND C13
CLARION COAL BED

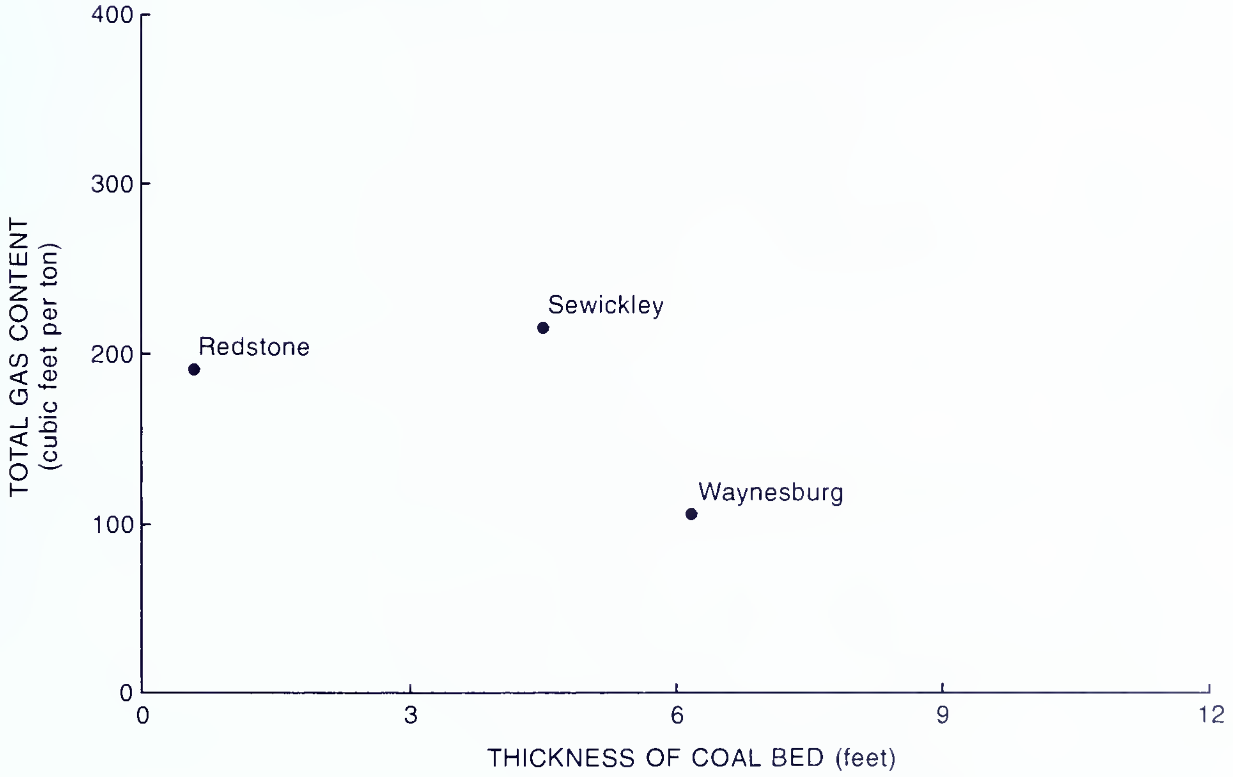

FAYETTE COUNTY, DRILL HOLES C3, C4, AND C14
BROOKVILLE COAL BED
TOTAL GAS CONTENT (cubic feet per ton)
400
300
200
100
0
0
300
600
900
1200
1500
DEPTH TO BASE OF COAL BED (feet)

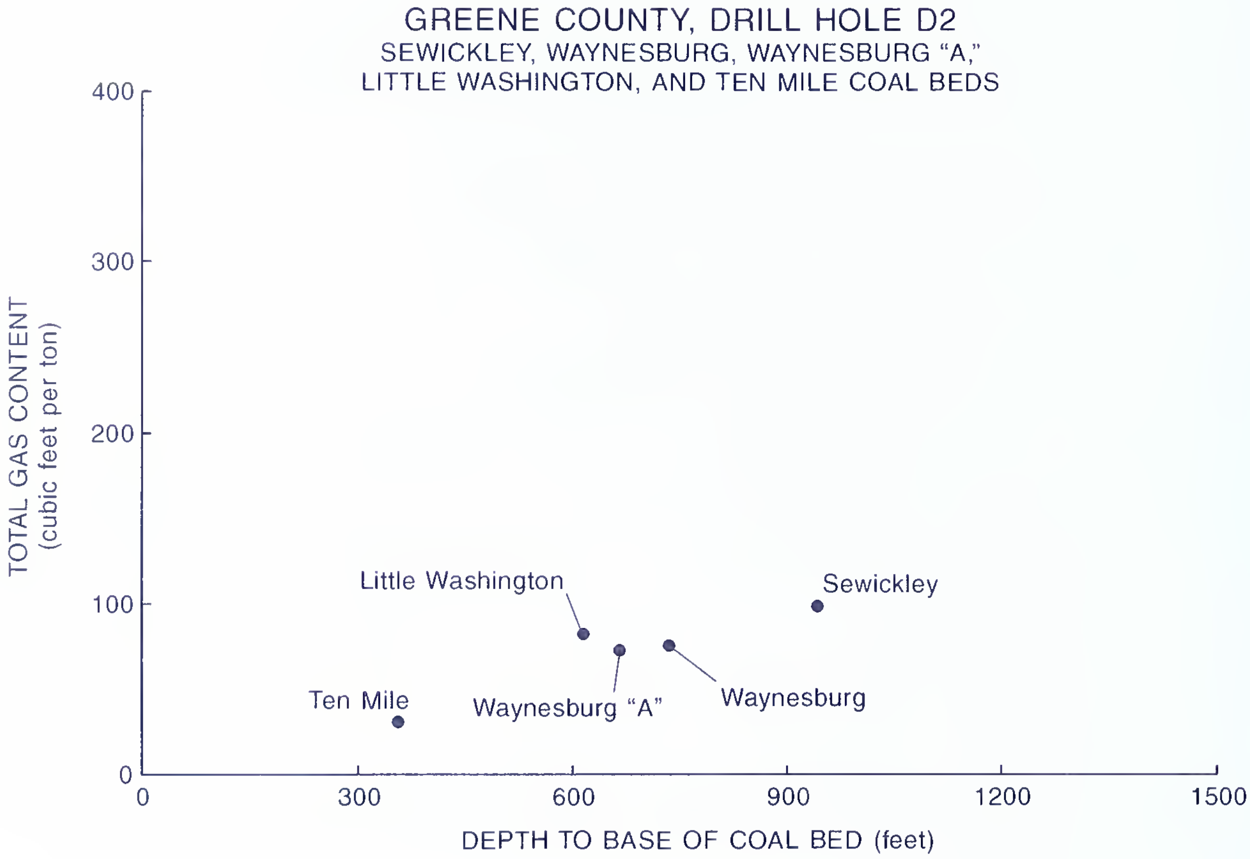

FAYETTE COUNTY, DRILL HOLES C3, C4, AND C14
BROOKVILLE COAL BED
TOTAL GAS CONTENT (cubic feet per ton)
400
300
200
100
0
0
3
6
9
12
THICKNESS OF COAL BED (feet)

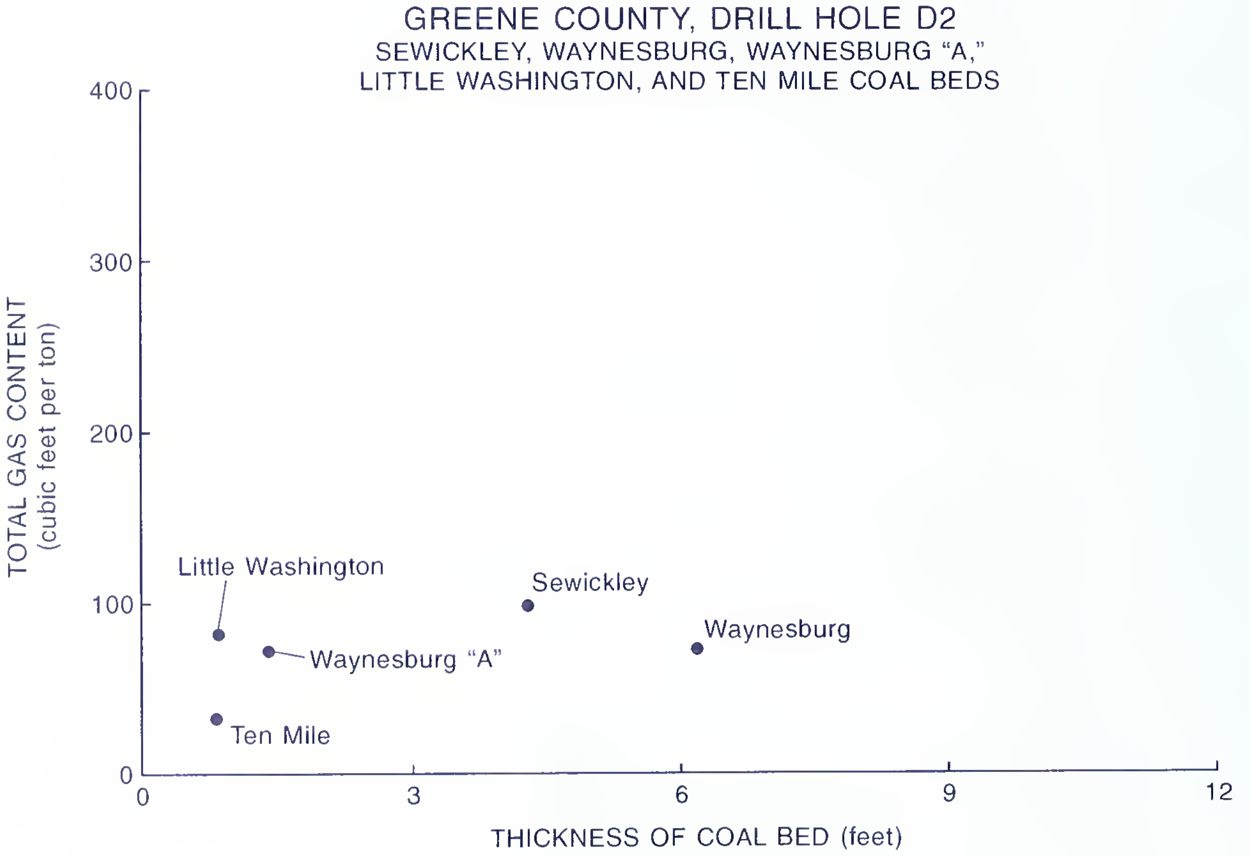
GREENE COUNTY, VENTILATION BOREHOLE D1
PITTSBURGH, PITTSBURGH RIDER, REDSTONE, SEWICKLEY, WAYNESBURG, AND WAYNESBURG "A" COAL BEDS

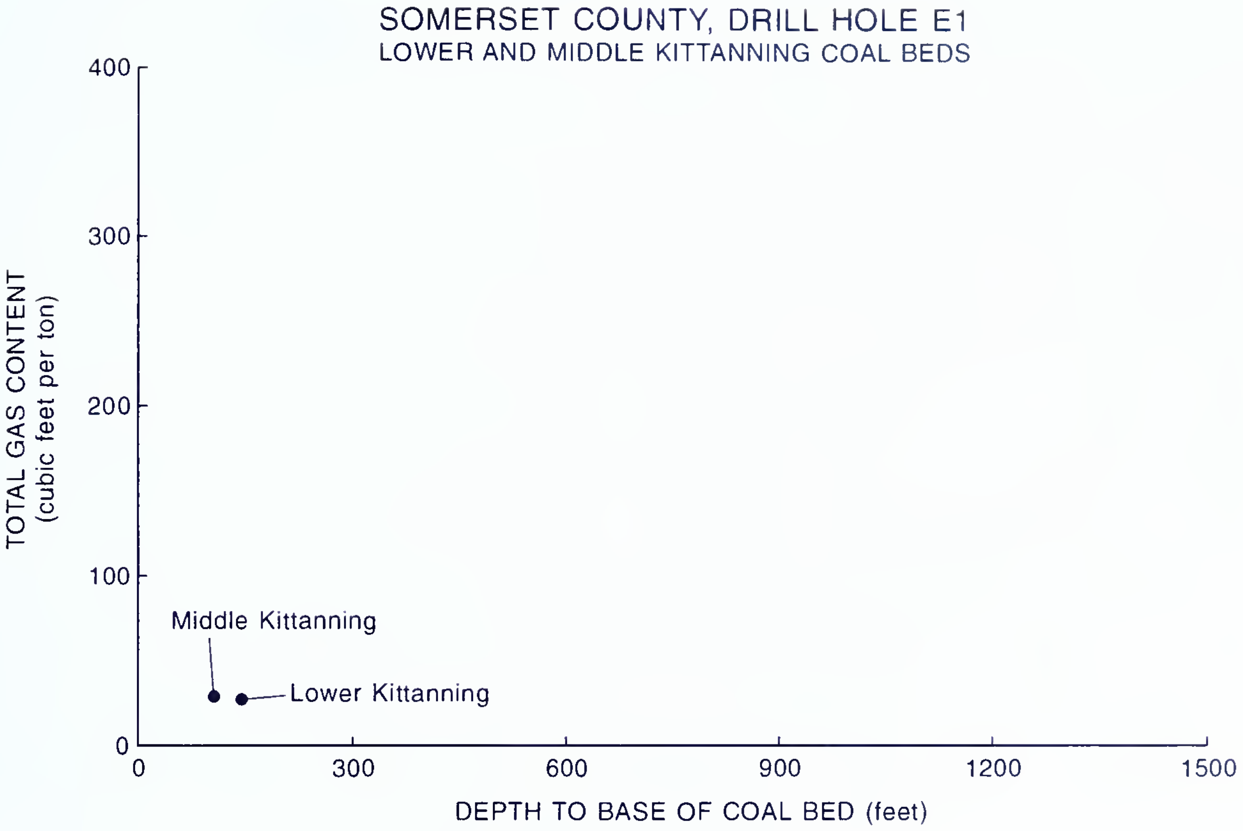


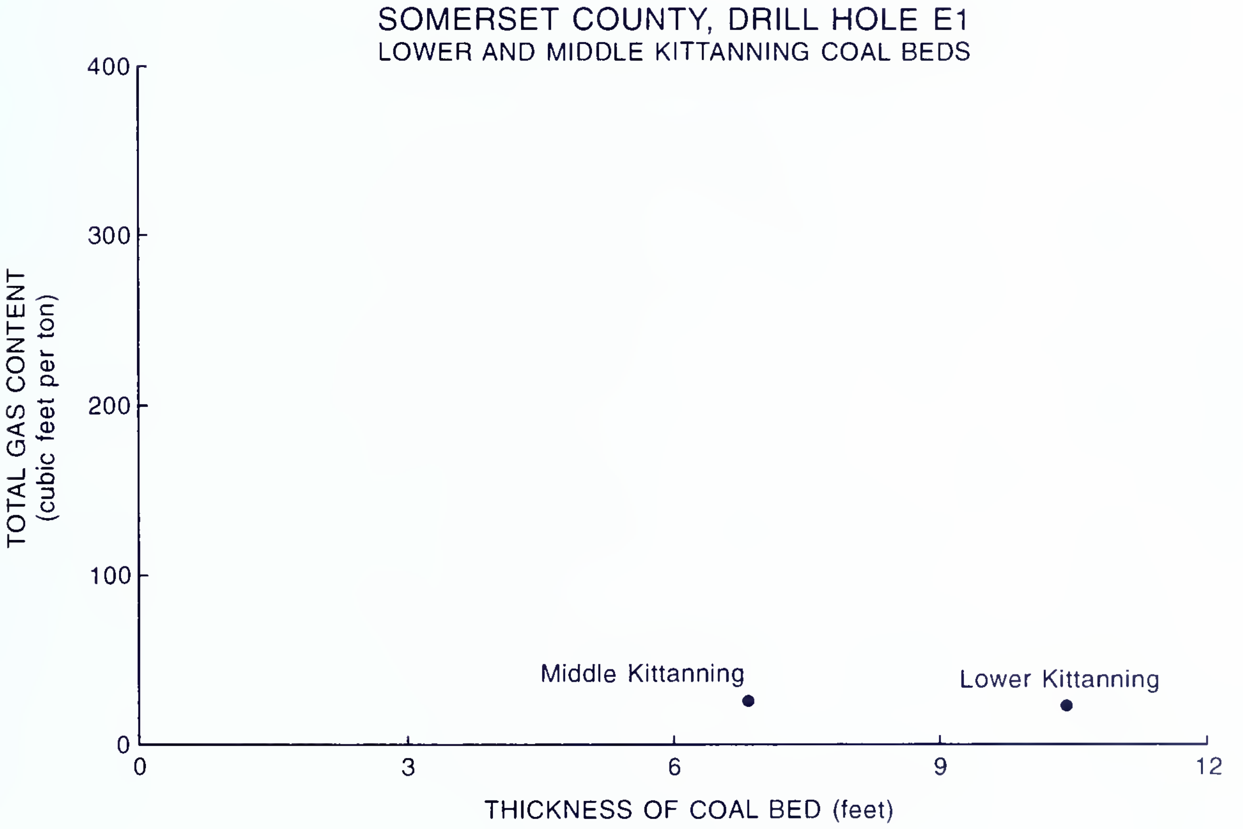
GREENE COUNTY, VENTILATION BOREHOLE D1
REDSTONE, SEWICKLEY, AND WAYNESBURG COAL BEDS

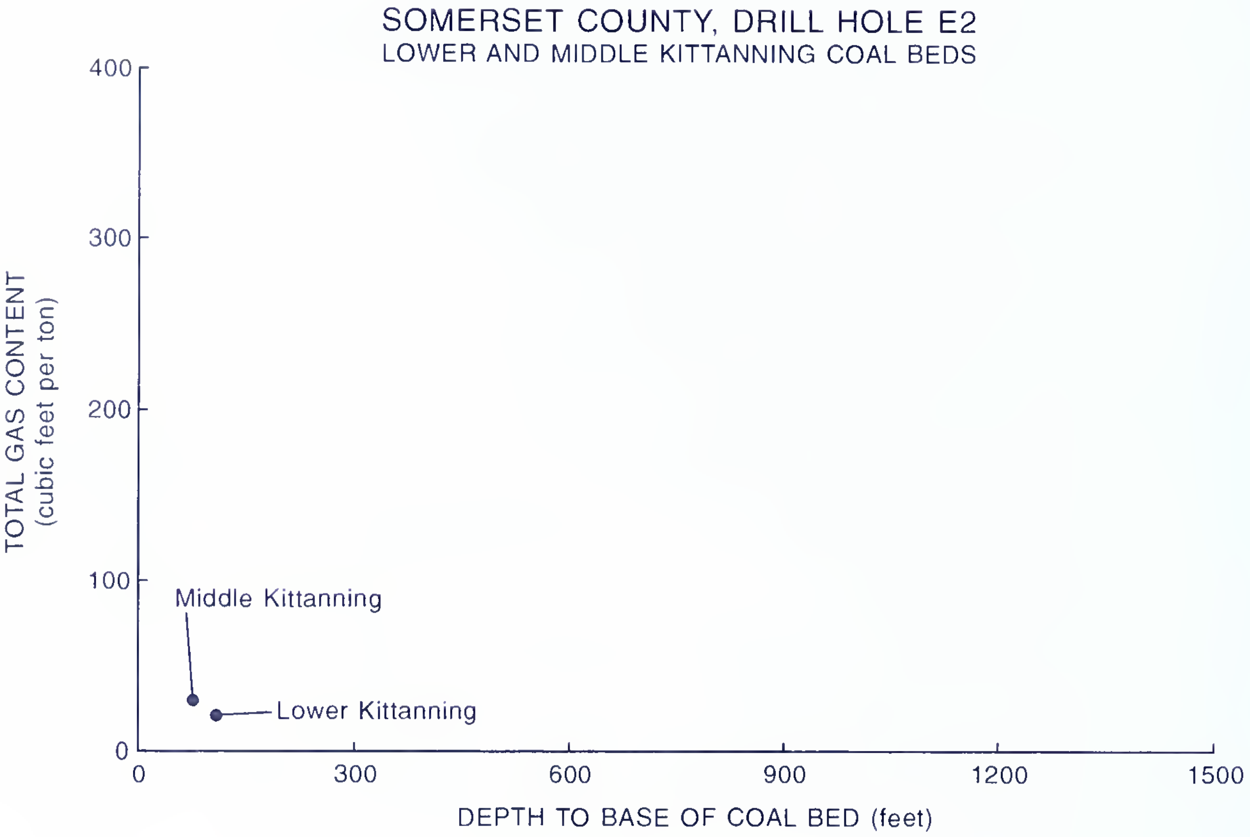


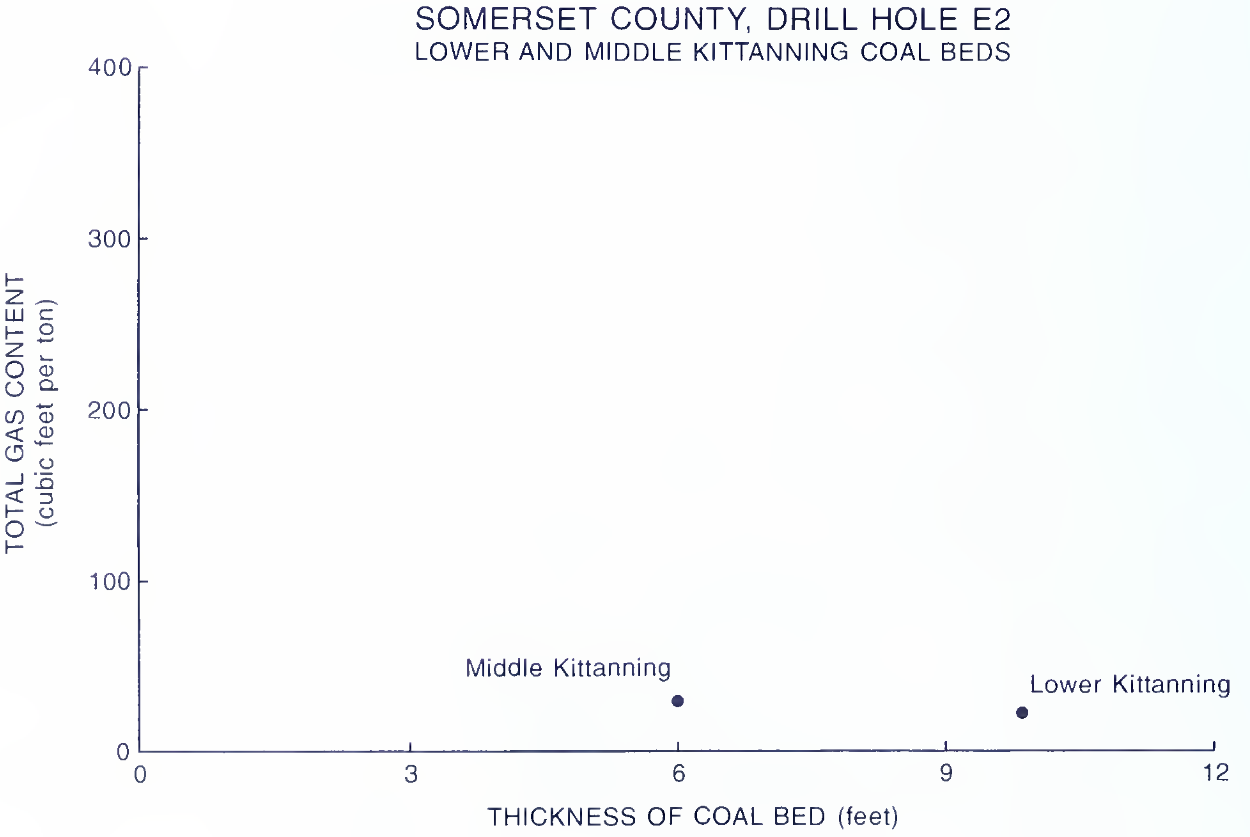

GREENE COUNTY, DRILL HOLE D2
SEWICKLEY, WAYNESBURG, WAYNESBURG "A,"
LITTLE WASHINGTON, AND TEN MILE COAL BEDS
TOTAL GAS CONTENT (cubic feet per ton)
400
300
200
100
0
Little Washington
Sewickley
Ten Mile
Waynesburg "A"
Waynesburg
0
300
600
900
1200
1500
DEPTH TO BASE OF COAL BED (feet)

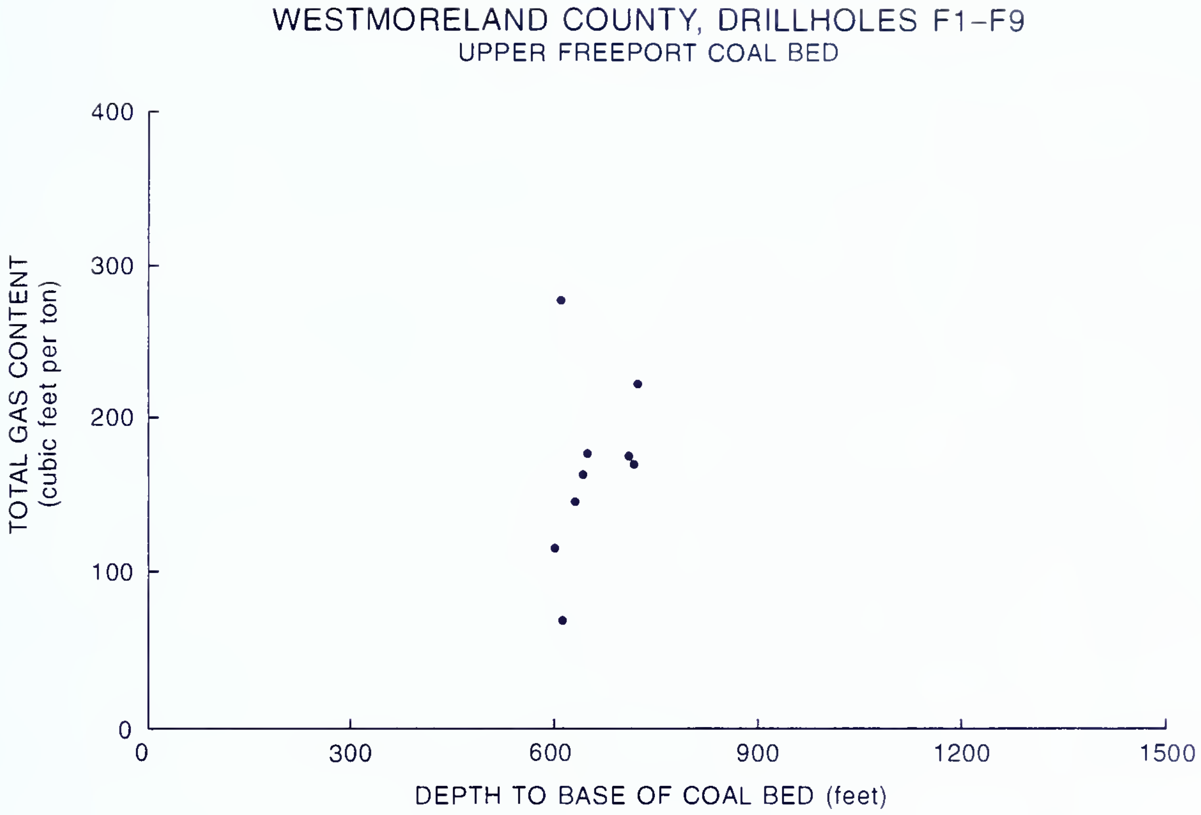

GREENE COUNTY, DRILL HOLE D2
SEWICKLEY, WAYNESBURG, WAYNESBURG "A,"
LITTLE WASHINGTON, AND TEN MILE COAL BEDS
TOTAL GAS CONTENT (cubic feet per ton)
400
300
200
100
0
Little Washington
Sewickley
Waynesburg
Waynesburg "A"
Ten Mile
0
3
6
9
12
THICKNESS OF COAL BED (feet)


SOMERSET COUNTY, DRILL HOLE E1
LOWER AND MIDDLE KITTANNING COAL BEDS
TOTAL GAS CONTENT (cubic feet per ton)
400
300
200
100
0
Middle Kittanning
Lower Kittanning
0
300
600
900
1200
1500
DEPTH TO BASE OF COAL BED (feet)

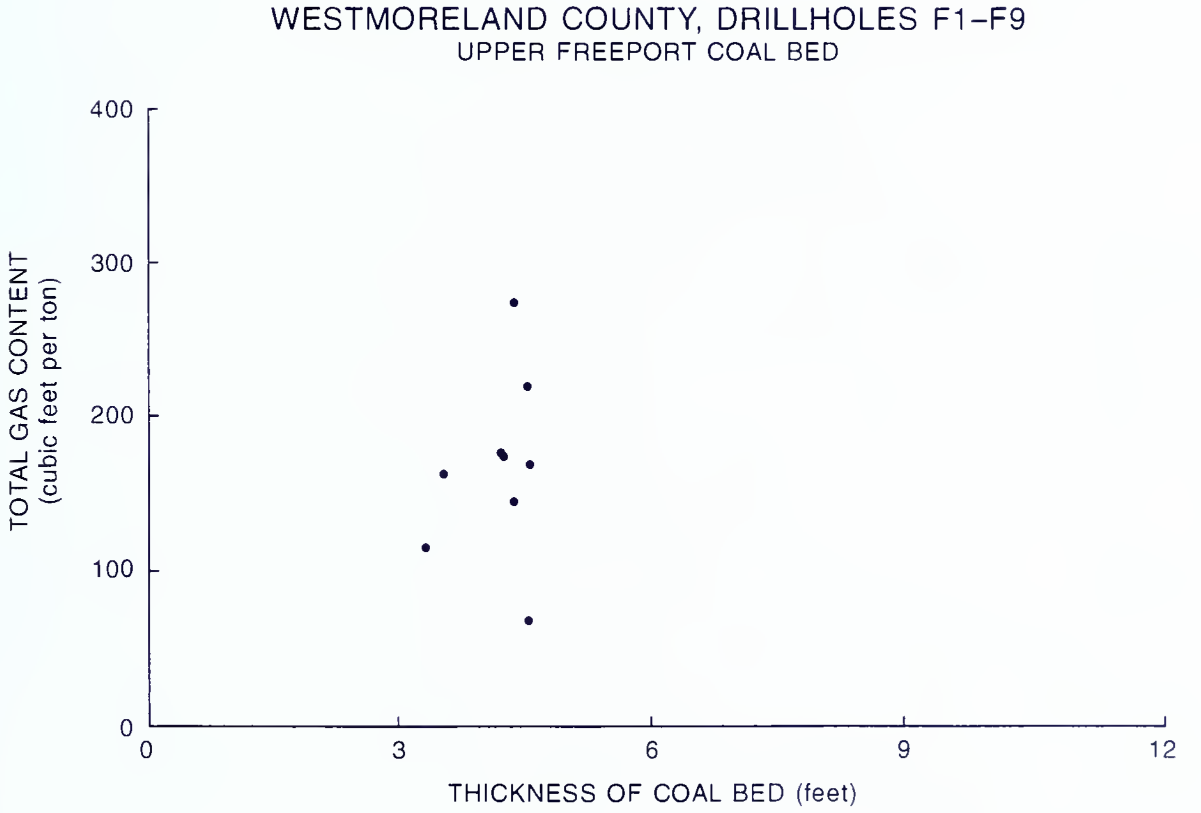

SOMERSET COUNTY, DRILL HOLE E1
LOWER AND MIDDLE KITTANNING COAL BEDS
TOTAL GAS CONTENT (cubic feet per ton)
400
300
200
100
0
Middle Kittanning
Lower Kittanning
0
3
6
9
12
THICKNESS OF COAL BED (feet)


SOMERSET COUNTY, DRILL HOLE E2
LOWER AND MIDDLE KITTANNING COAL BEDS
TOTAL GAS CONTENT (cubic feet per ton)
400
300
200
100
0
Middle Kittanning
Lower Kittanning
0
300
600
900
1200
1500
DEPTH TO BASE OF COAL BED (feet)


SOMERSET COUNTY, DRILL HOLE E2
LOWER AND MIDDLE KITTANNING COAL BEDS
TOTAL GAS CONTENT (cubic feet per ton)
400
300
200
100
0
Middle Kittanning
Lower Kittanning
0
3
6
9
12
THICKNESS OF COAL BED (feet)

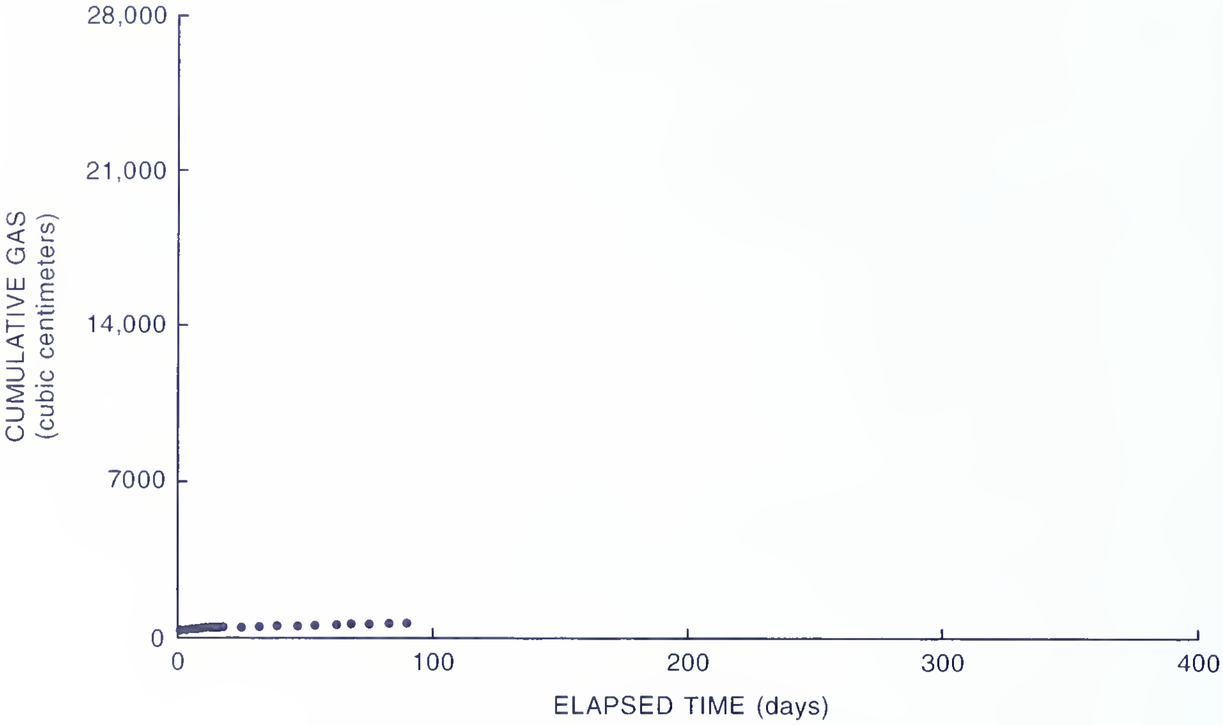


WESTMORELAND COUNTY, DRILLHOLES F1–F9
UPPER FREEPORT COAL BED

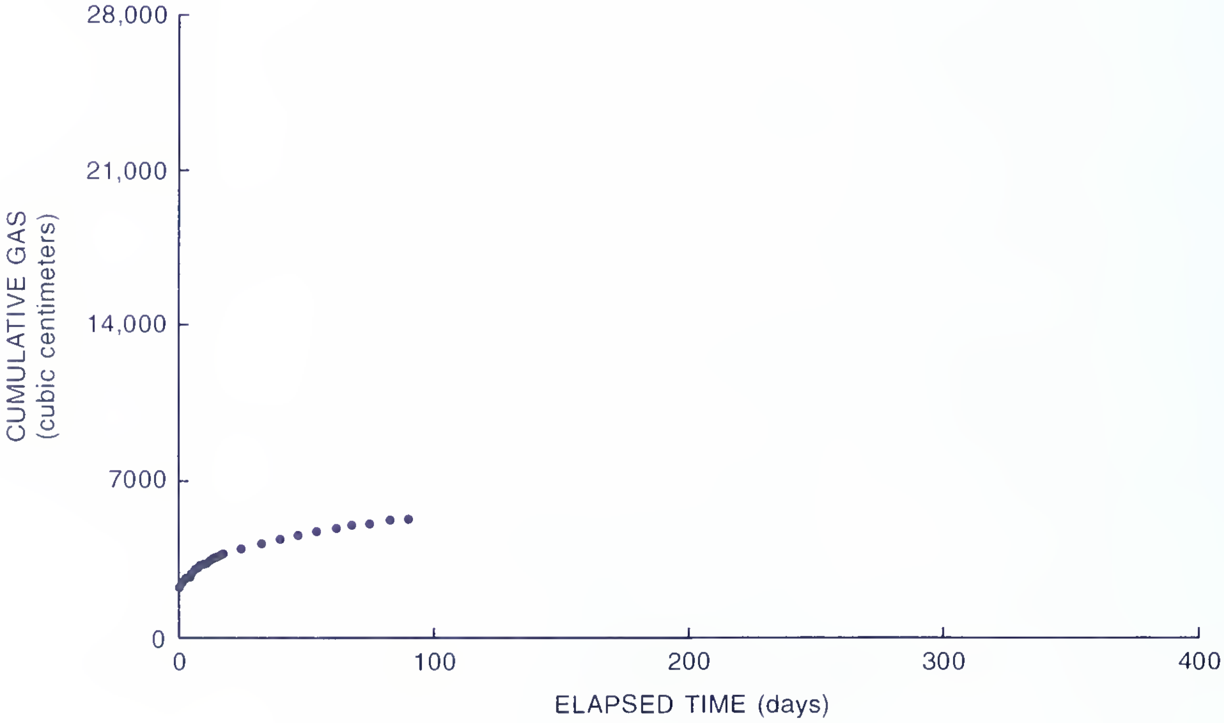


WESTMORELAND COUNTY, DRILLHOLES F1–F9
UPPER FREEPORT COAL BED

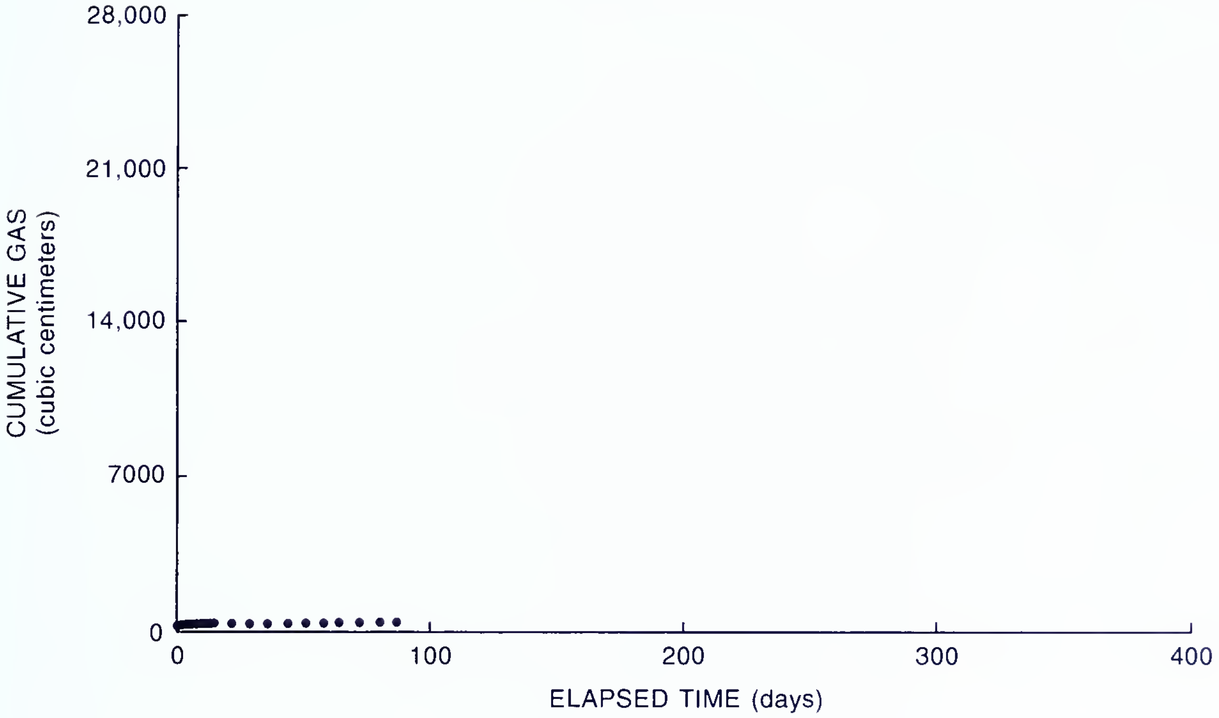
The following graphs show the cumulative gas amount versus elapsed time obtained from the direct methed of testing of coal beds. The coal samples were taken from the new drill holes in Armstrong, Cambria, Greene, and Somerset Counties.



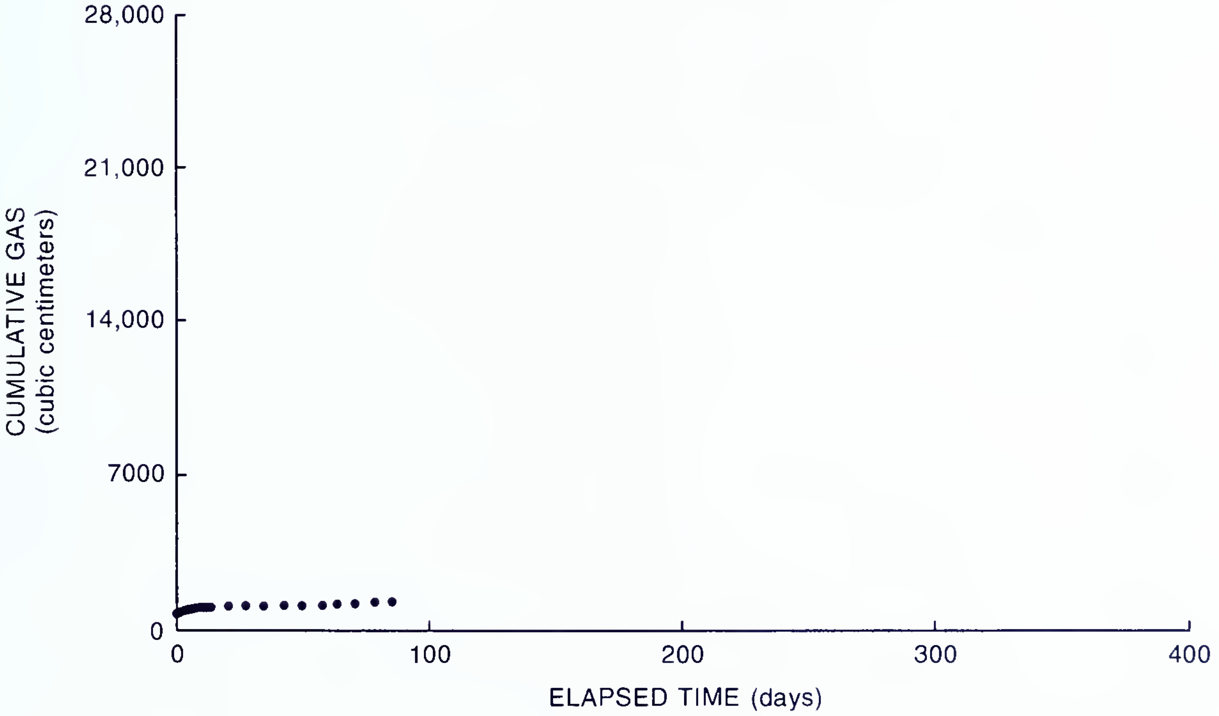
ARMSTRONG COUNTY, DRILL HOLE A1
UPPER KITTANNING COAL BED



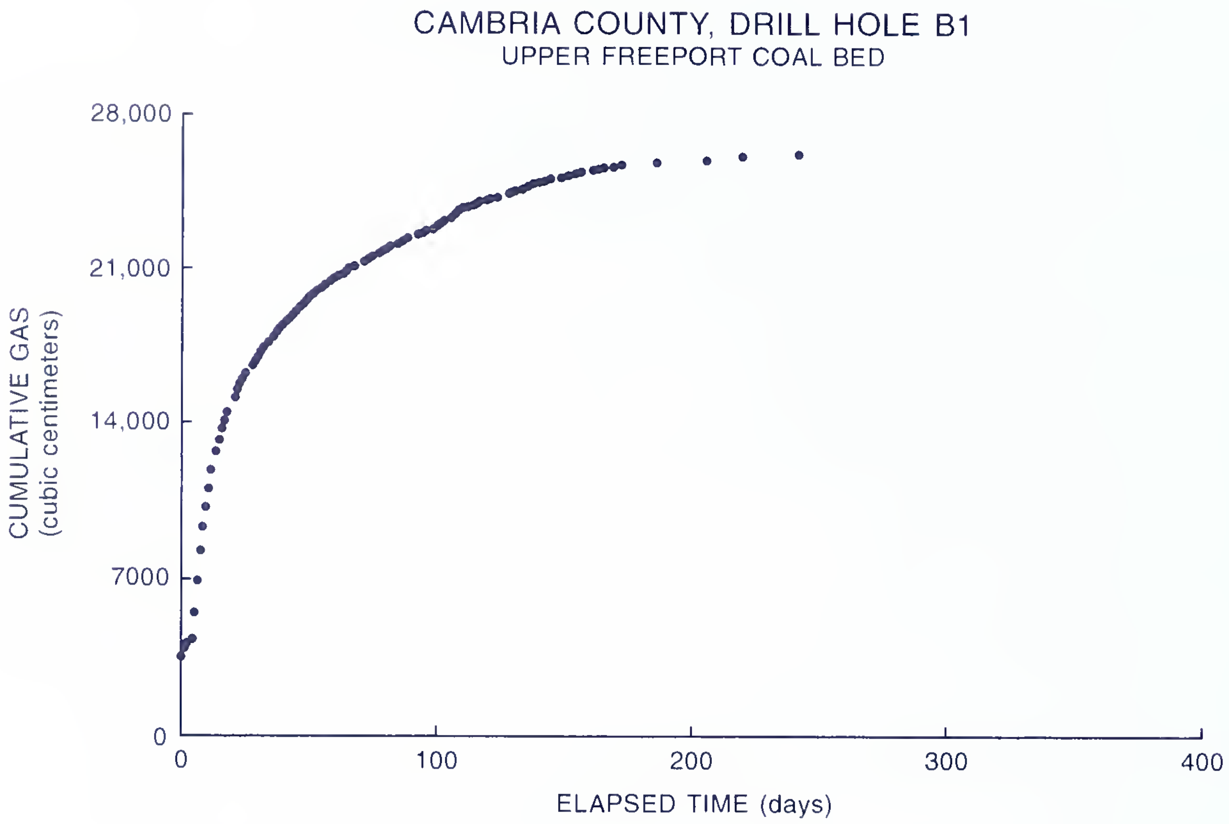
ARMSTRONG COUNTY, DRILL HOLE A1
LOWER KITTANNING COAL BED

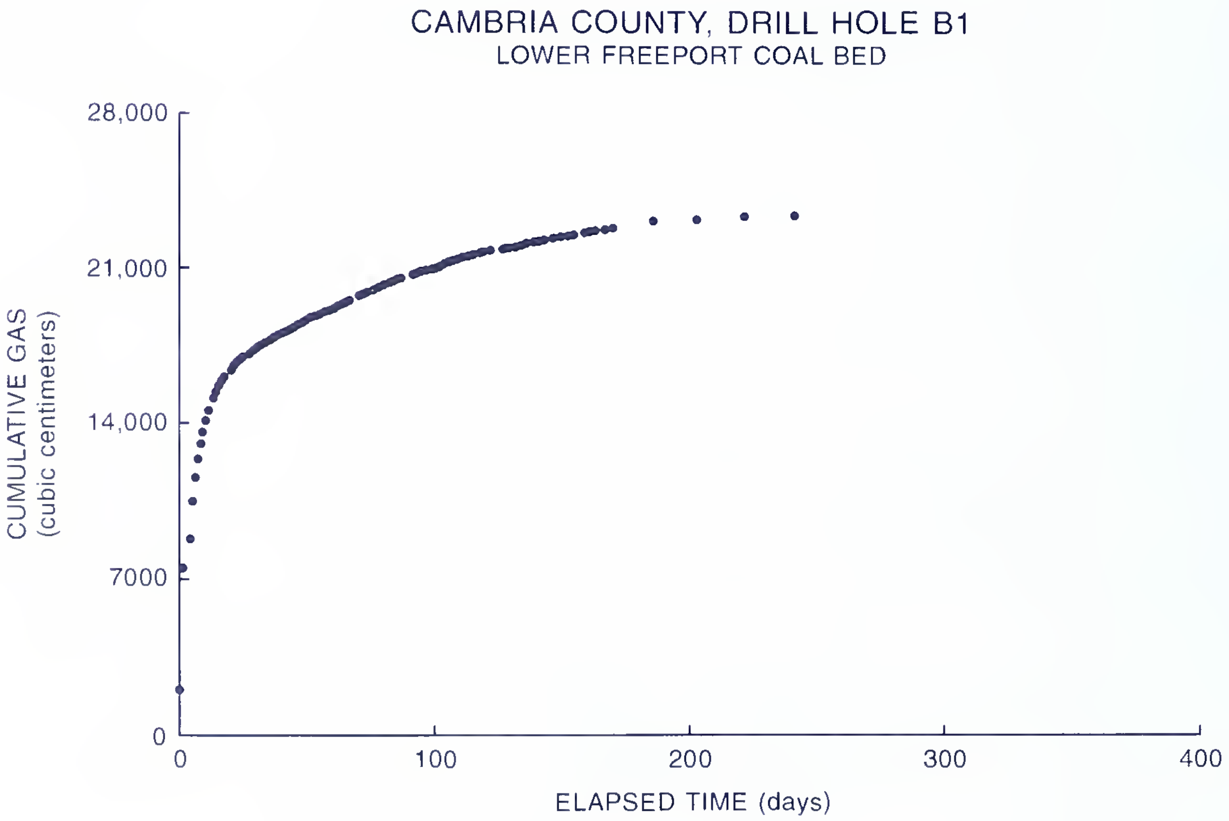


ARMSTRONG COUNTY, DRILL HOLE A2
UPPER KITTANNING COAL BED

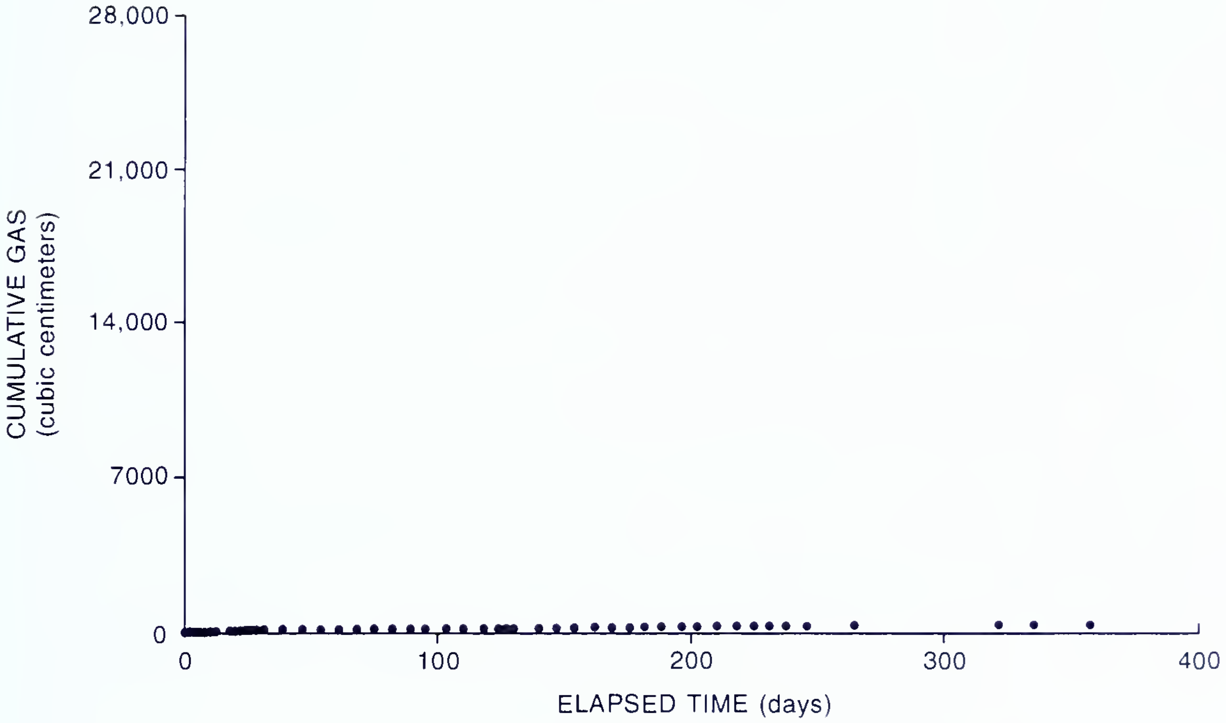


ARMSTRONG COUNTY, DRILL HOLE A2
LOWER KITTANNING COAL BED

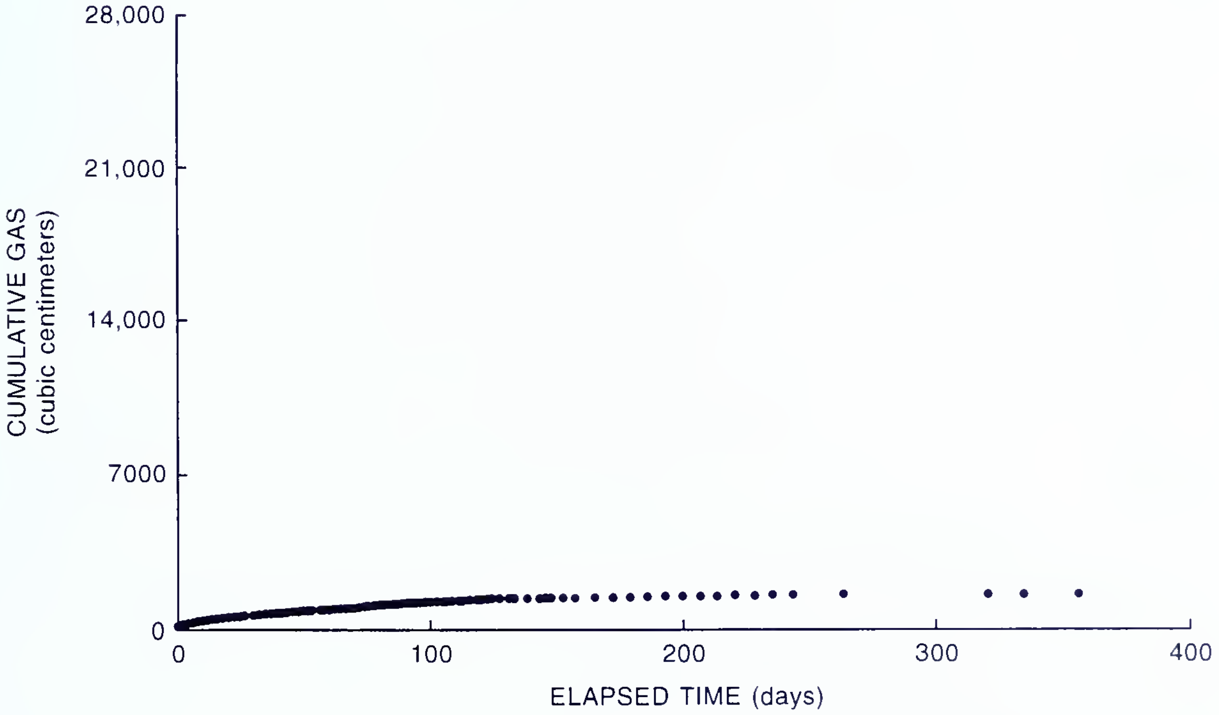

CAMBRIA COUNTY, DRILL HOLE B1
UPPER FREEPORT COAL BED
CUMULATIVE GAS (cubic centimeters)
28,000
21,000
14,000
7000
0
0
100
200
300
400
ELAPSED TIME (days)

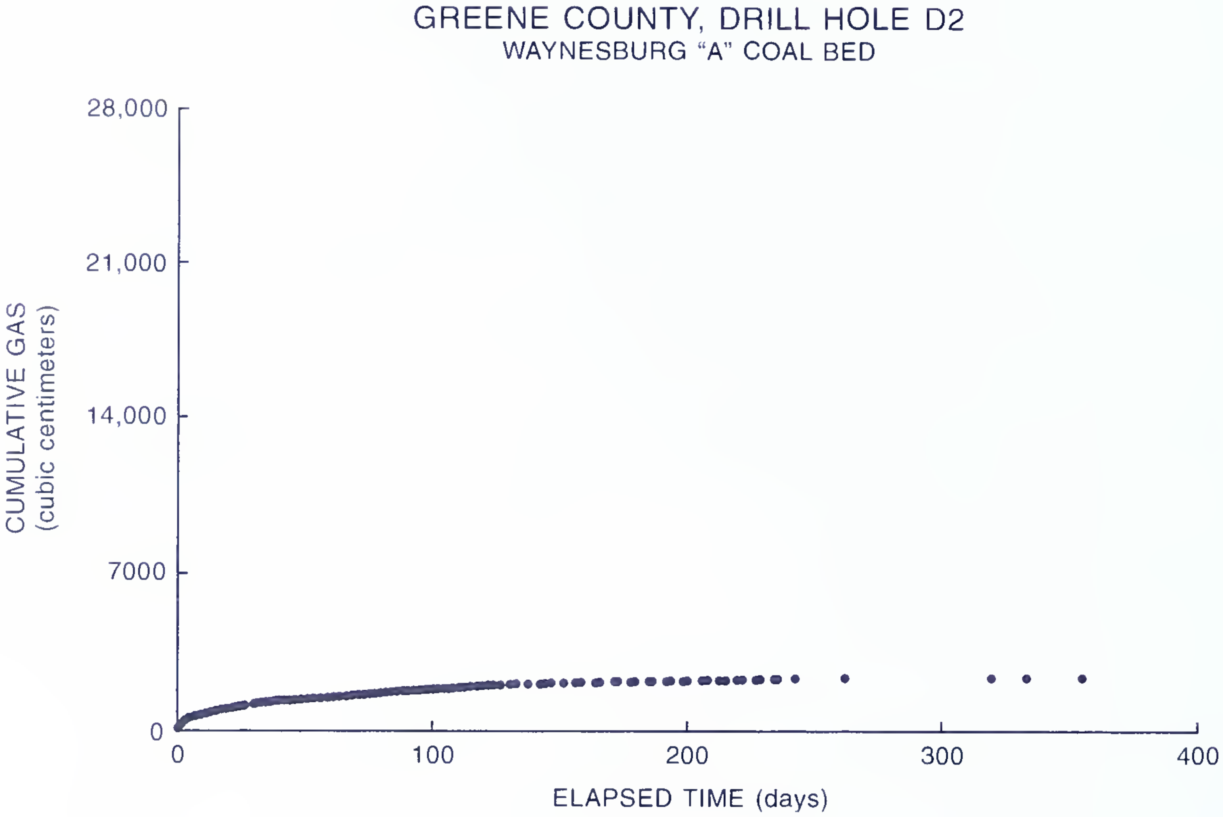

CAMBRIA COUNTY, DRILL HOLE B1
LOWER FREEPORT COAL BED
CUMULATIVE GAS (cubic centimeters)
28,000
21,000
14,000
7000
0
0
100
200
300
400
ELAPSED TIME (days)

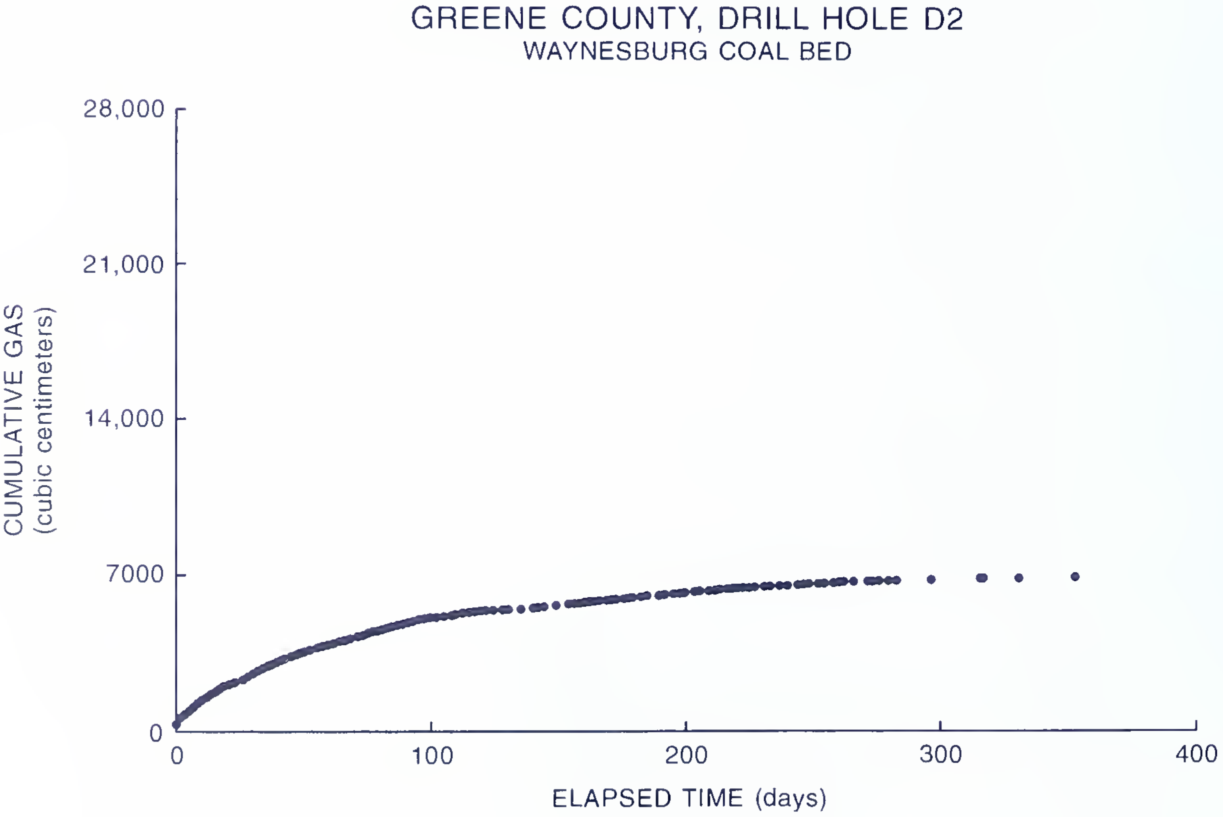
GREENE COUNTY, DRILL HOLE D2
TENMILE COAL BED

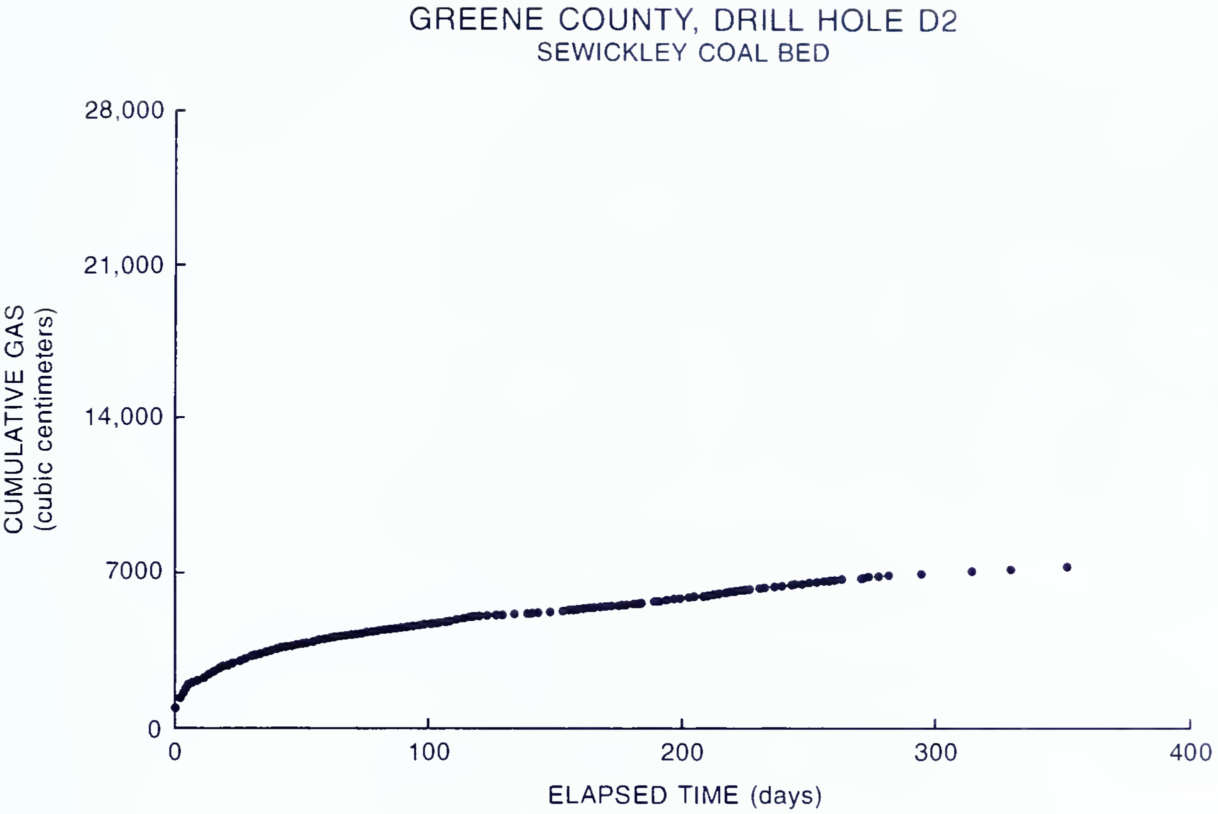


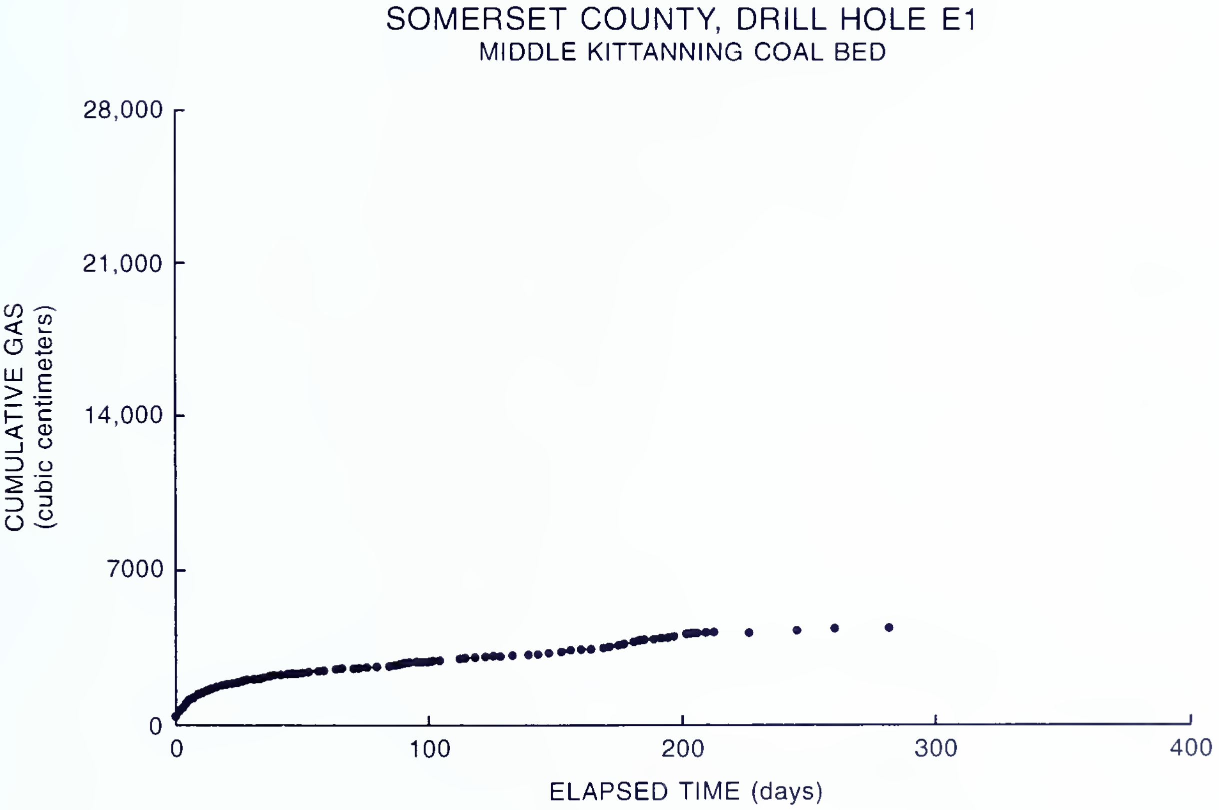
GREENE COUNTY, DRILL HOLE D2
LITTLE WASHINGTON COAL BED

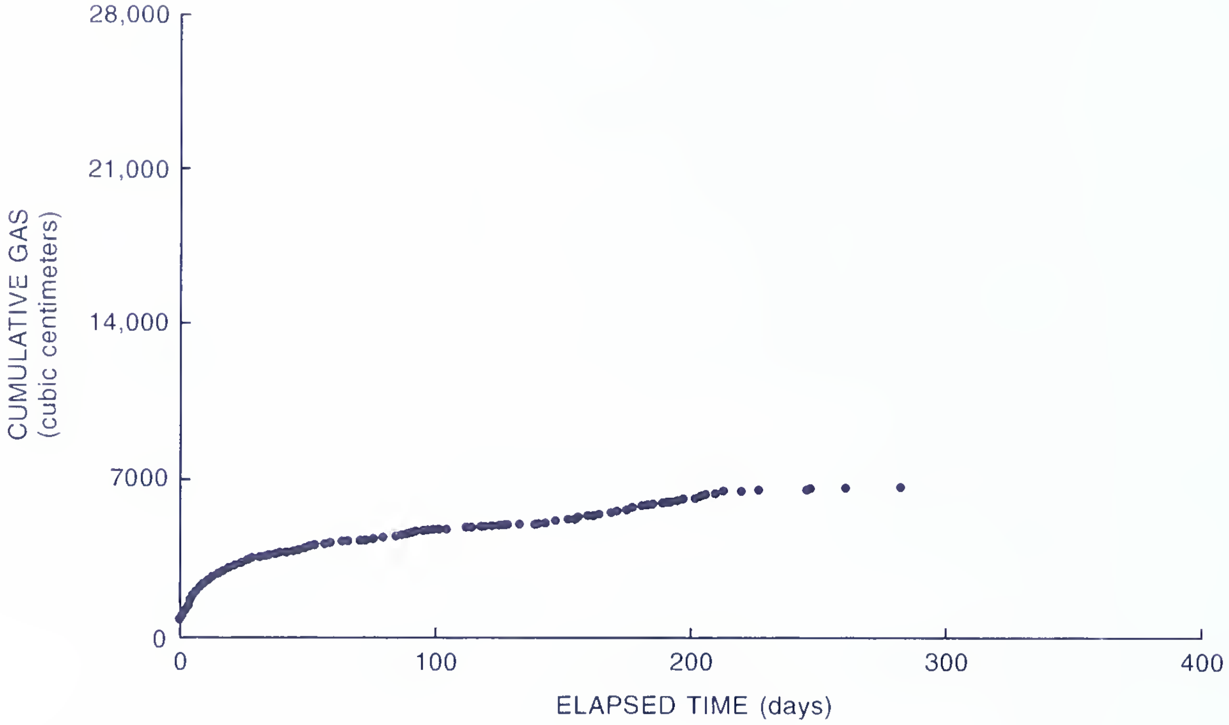


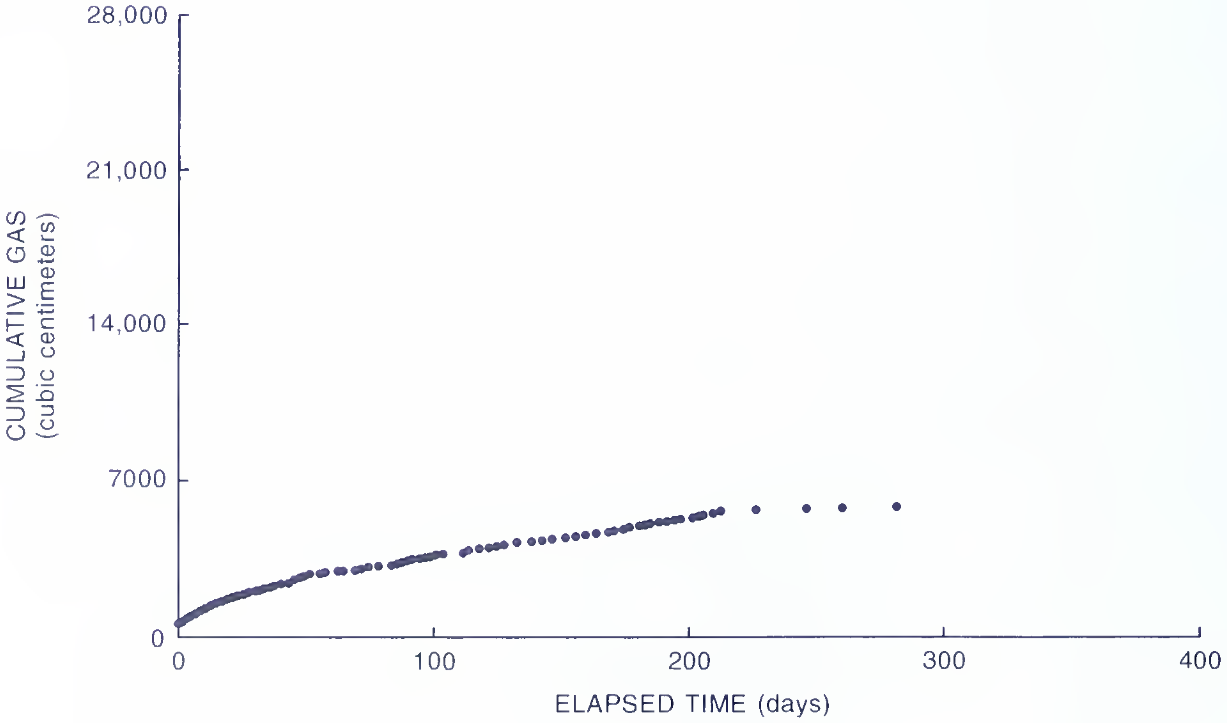

GREENE COUNTY, DRILL HOLE D2
WAYNESBURG "A" COAL BED
CUMULATIVE GAS (cubic centimeters)
28,000
21,000
14,000
7000
0
0
100
200
300
400
ELAPSED TIME (days)

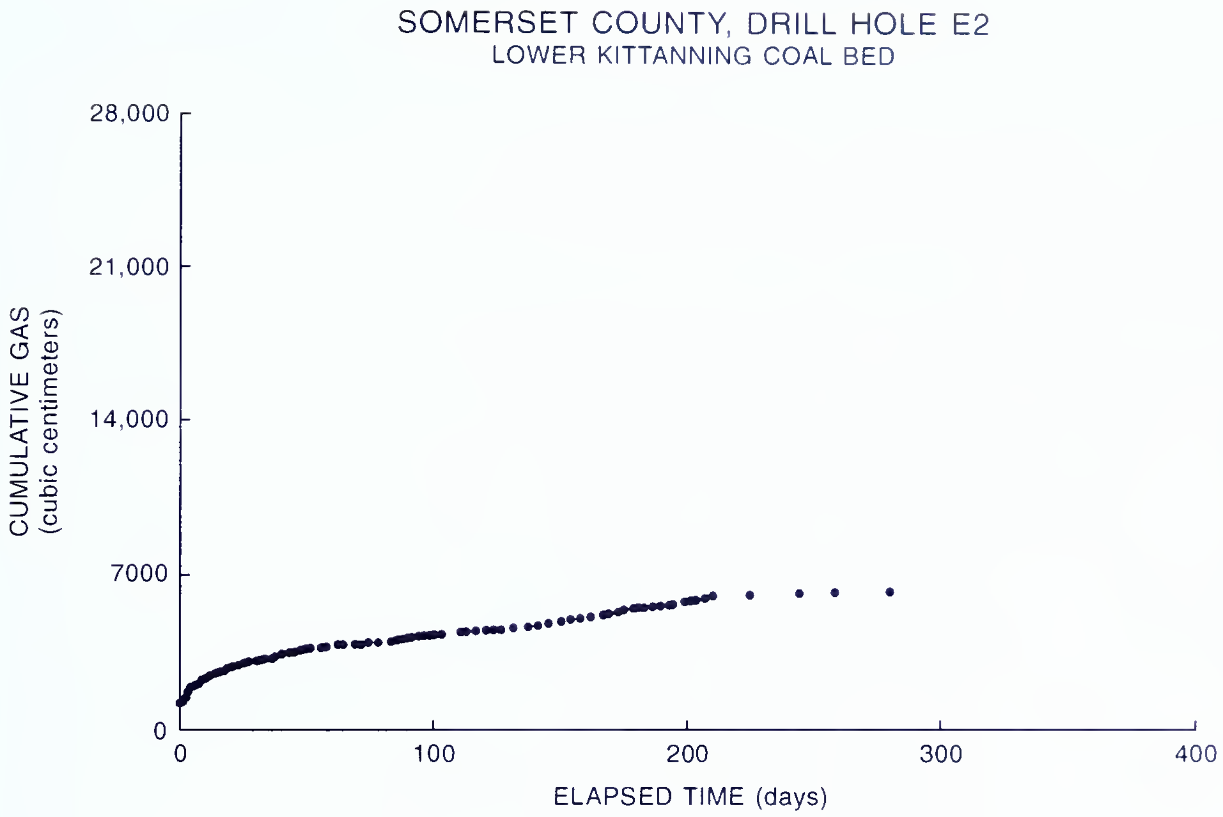

GREENE COUNTY, DRILL HOLE D2
WAYNESBURG COAL BED
CUMULATIVE GAS (cubic centimeters)
28,000
21,000
14,000
7000
0
0
100
200
300
400
ELAPSED TIME (days)


GREENE COUNTY, DRILL HOLE D2
SEWICKLEY COAL BED
CUMULATIVE GAS (cubic centimeters)
28,000
21,000
14,000
7000
0
0
100
200
300
400
ELAPSED TIME (days)


SOMERSET COUNTY, DRILL HOLE E1
MIDDLE KITTANNING COAL BED
CUMULATIVE GAS (cubic centimeters)
28,000
21,000
14,000
7000
0
0
100
200
300
400
ELAPSED TIME (days)


SOMERSET COUNTY, DRILL HOLE E1
LOWER KITTANNING COAL BED

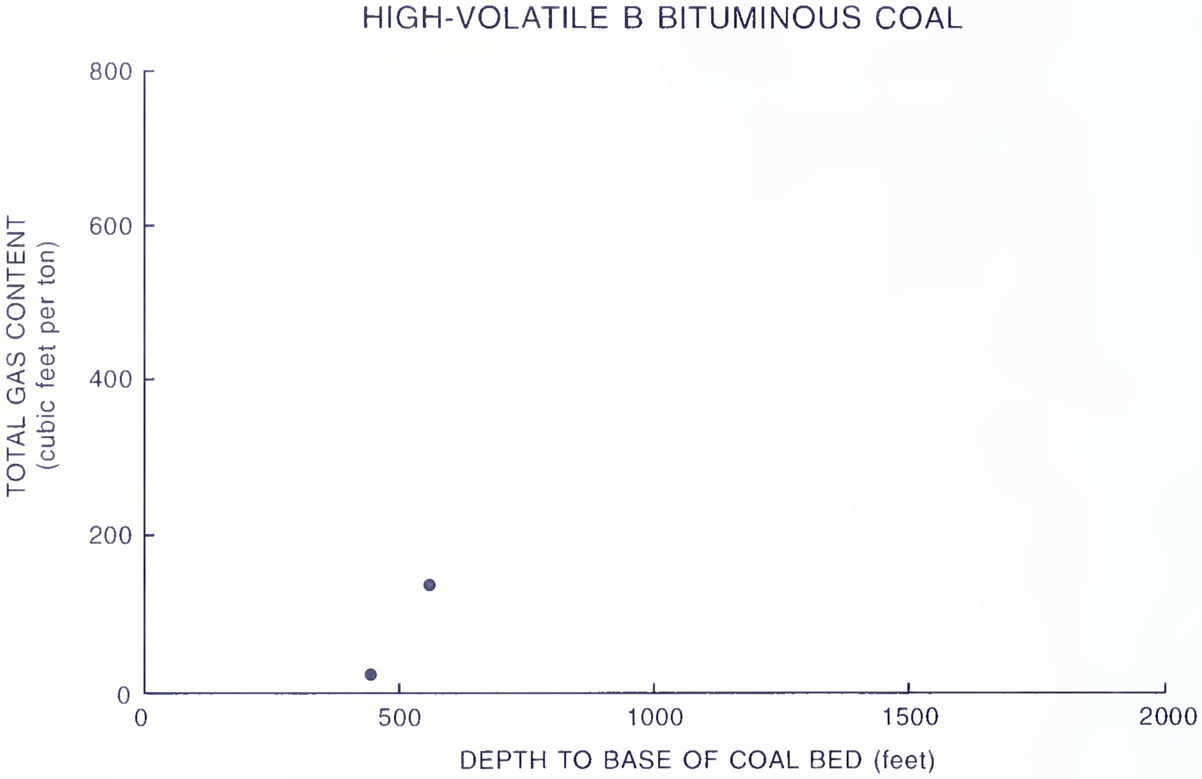

SOMERSET COUNTY, DRILL HOLE E2
MIDDLE KITTANNING COAL BED

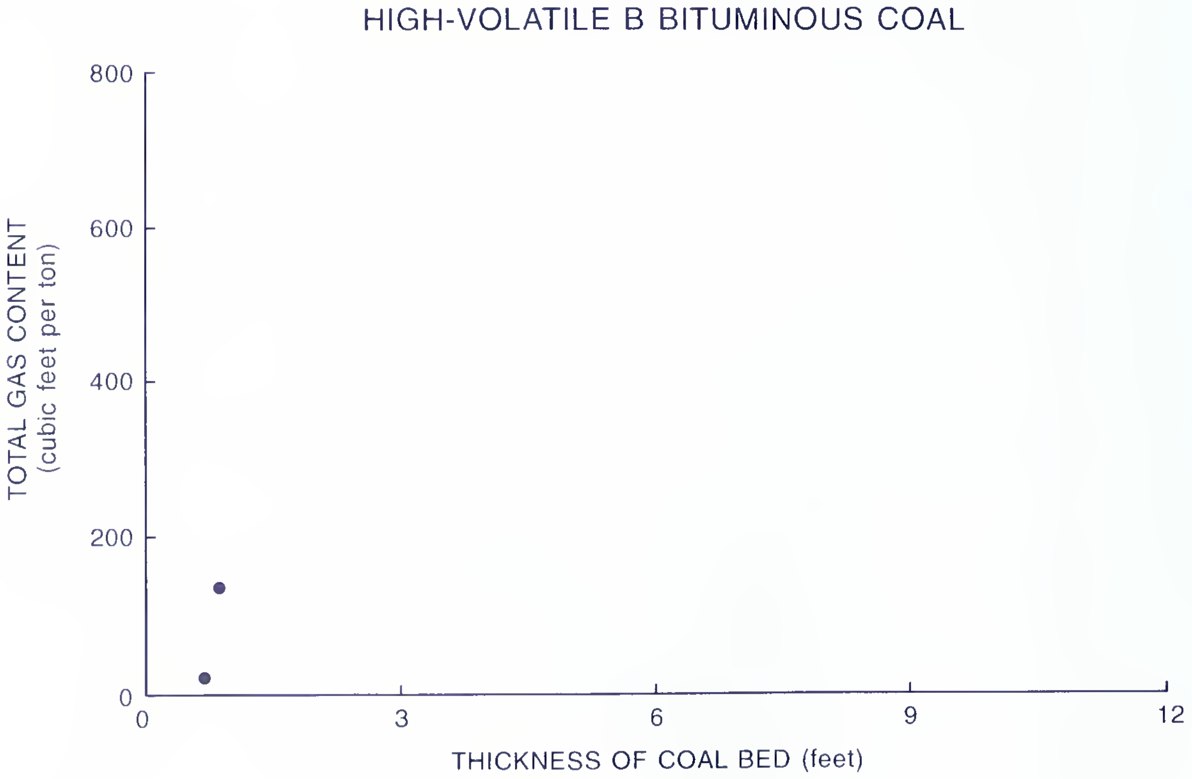

SOMERSET COUNTY, DRILL HOLE E2
LOWER KITTANNING COAL BED
CUMULATIVE GAS (cubic centimeters)
28,000
21,000
14,000
7000
0
0
100
200
300
400
ELAPSED TIME (days)

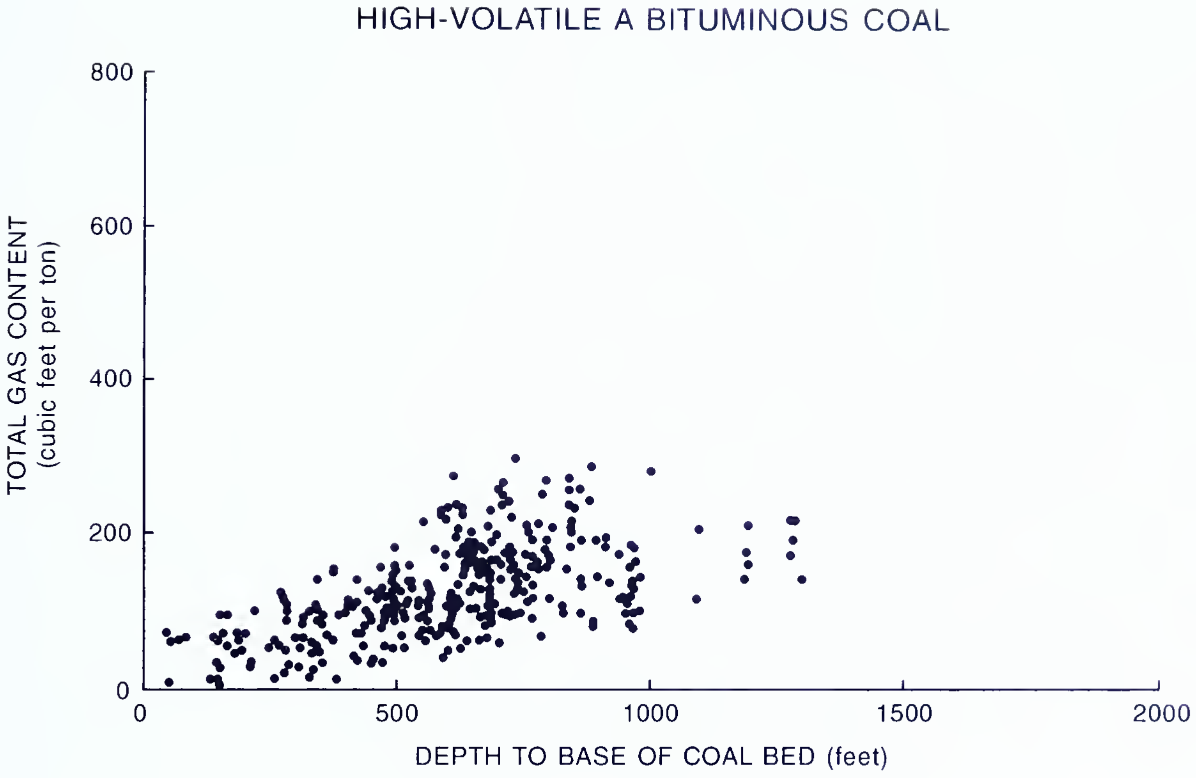
APPENDIX 4

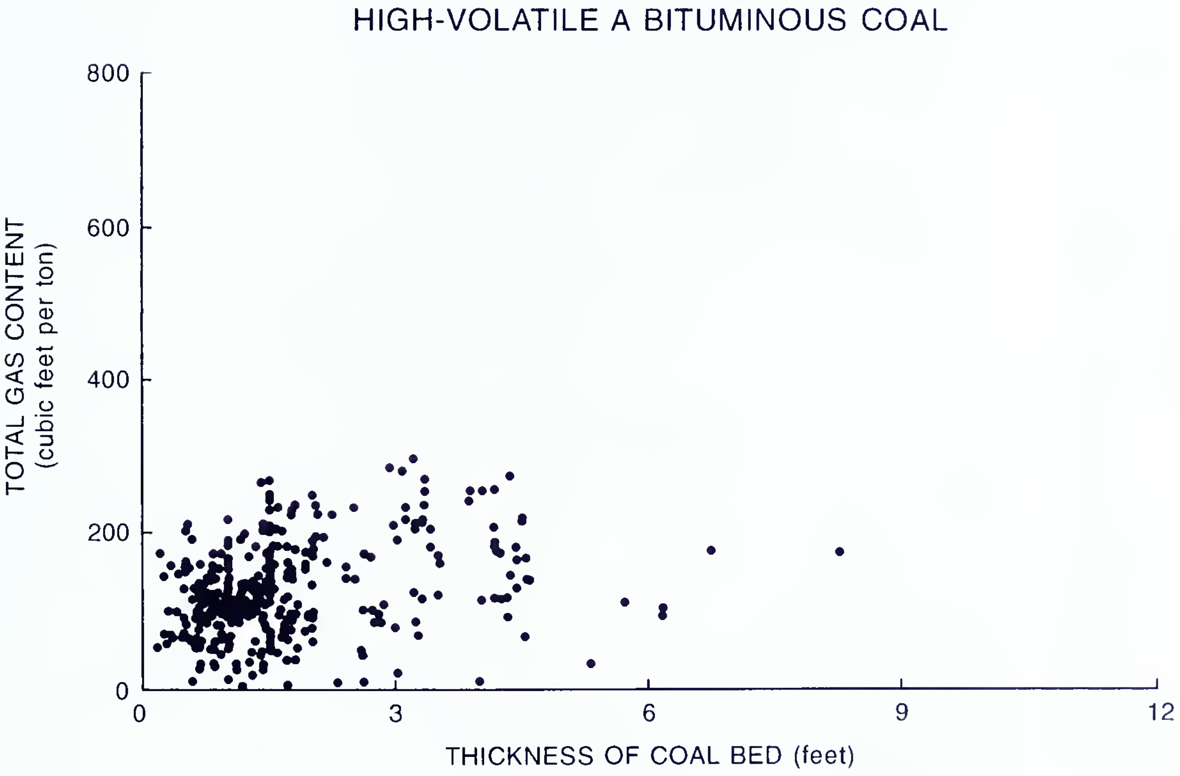
GAS CONTENT BASED ON COAL RANK

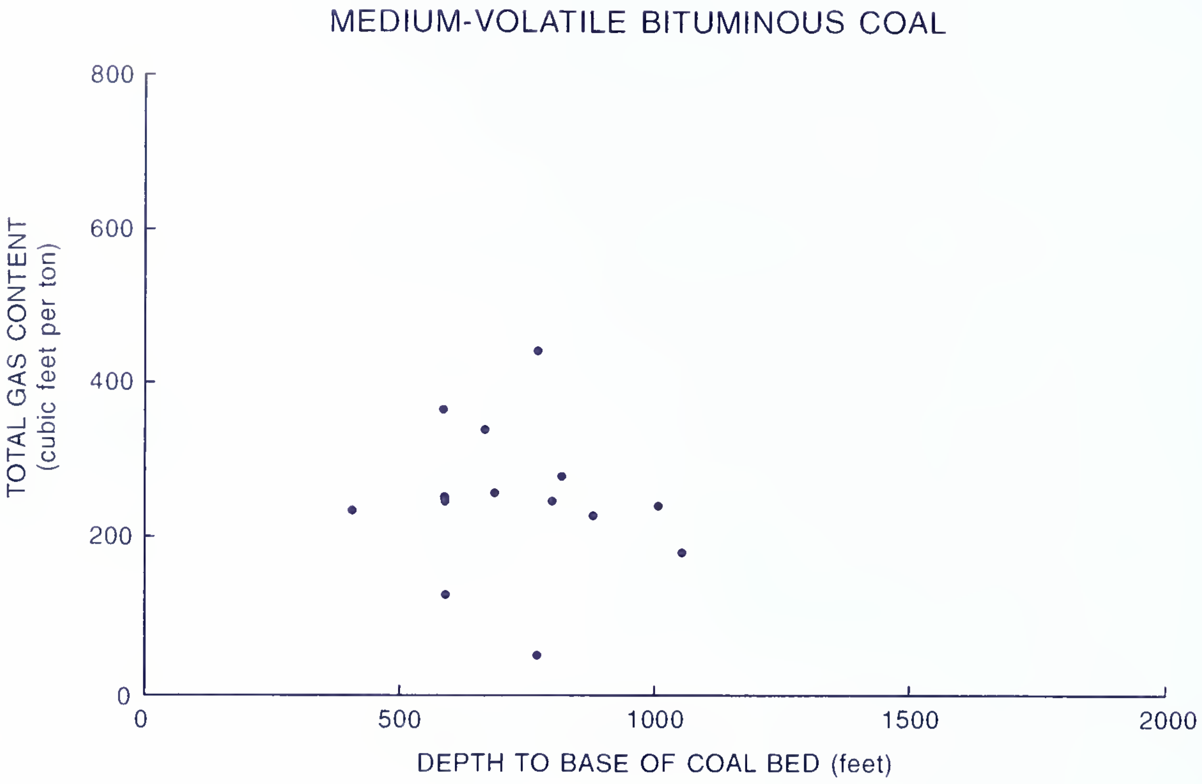
Appendix 4 contains graphs of total gas content versus depth to the base of the coal bed and total gas content versus the thickness of the coal bed based on the rank of the coals (both bituminous and anthracite) (some data from Diamond, LaScola, and Hyman, 1986, and U.S. Bureau of Mines, 1990).

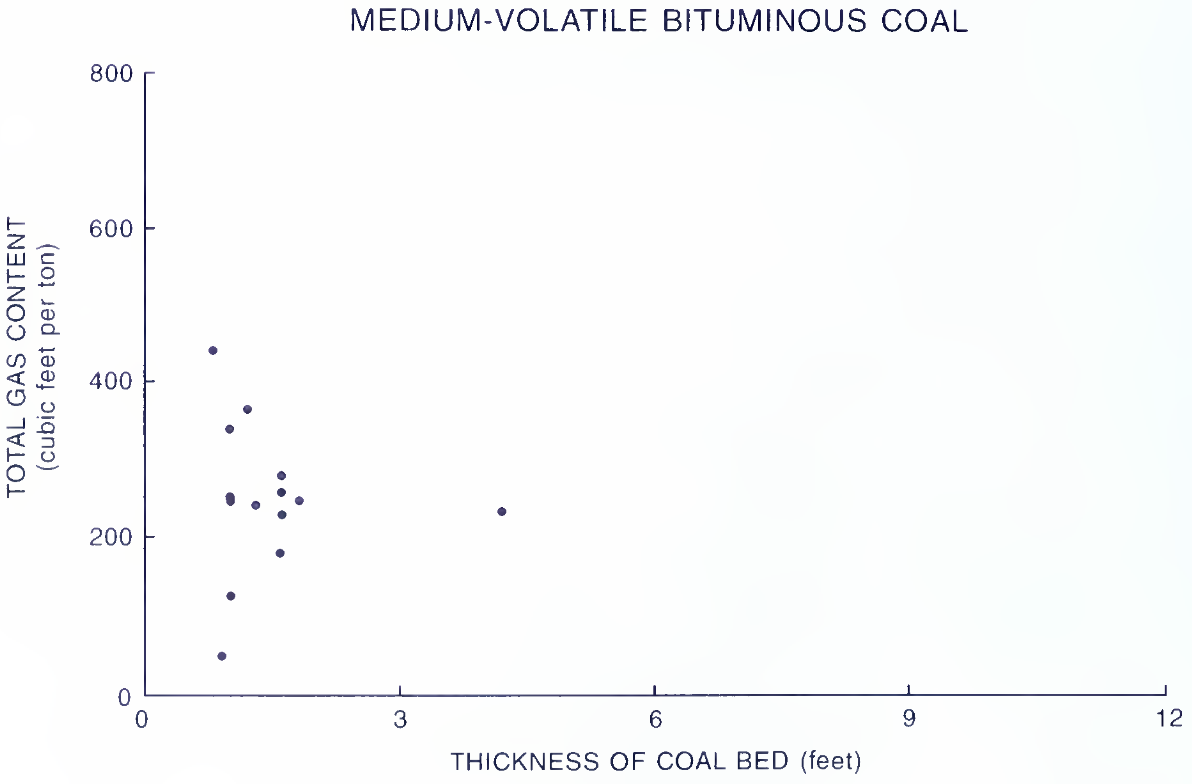


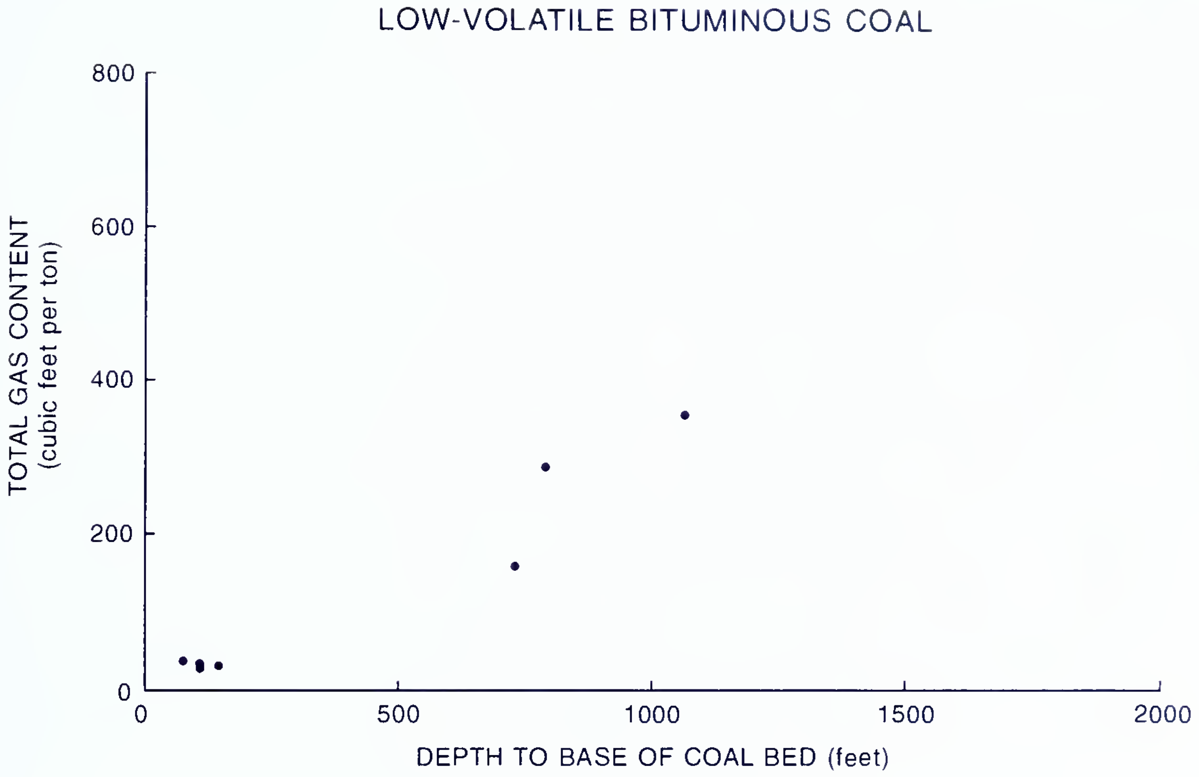


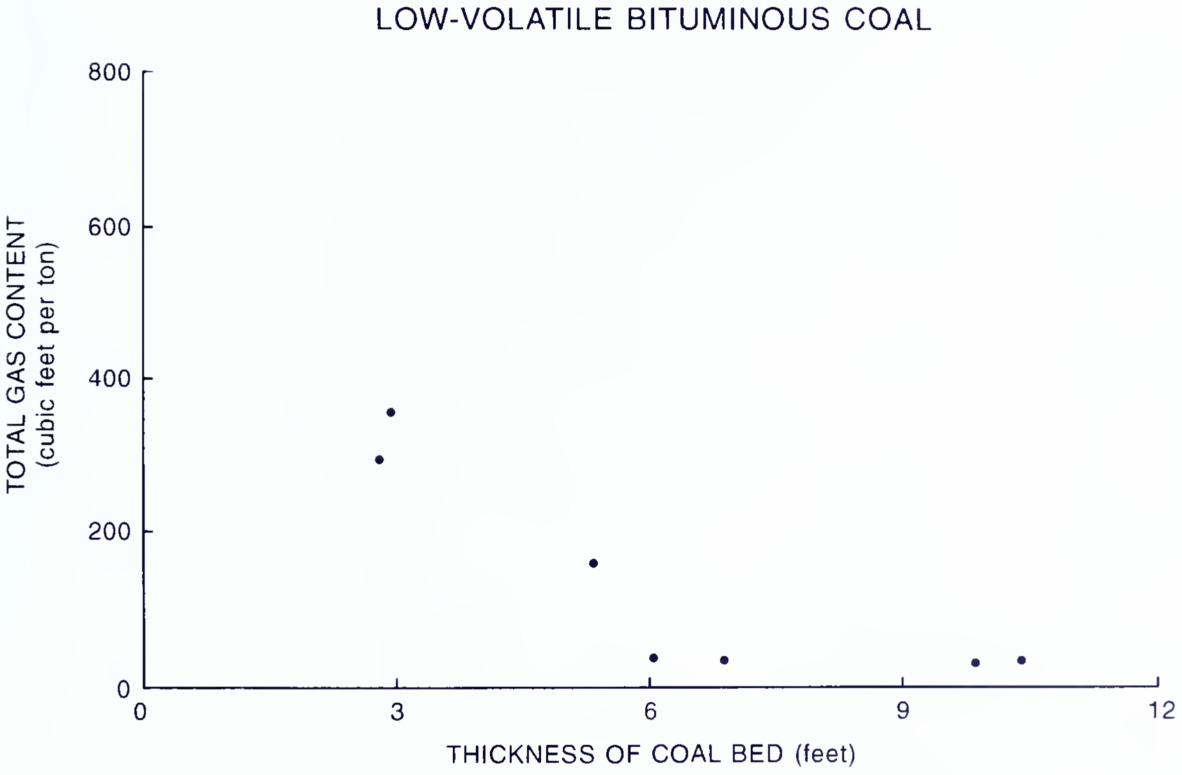

HIGH-VOLATILE A BITUMINOUS COAL

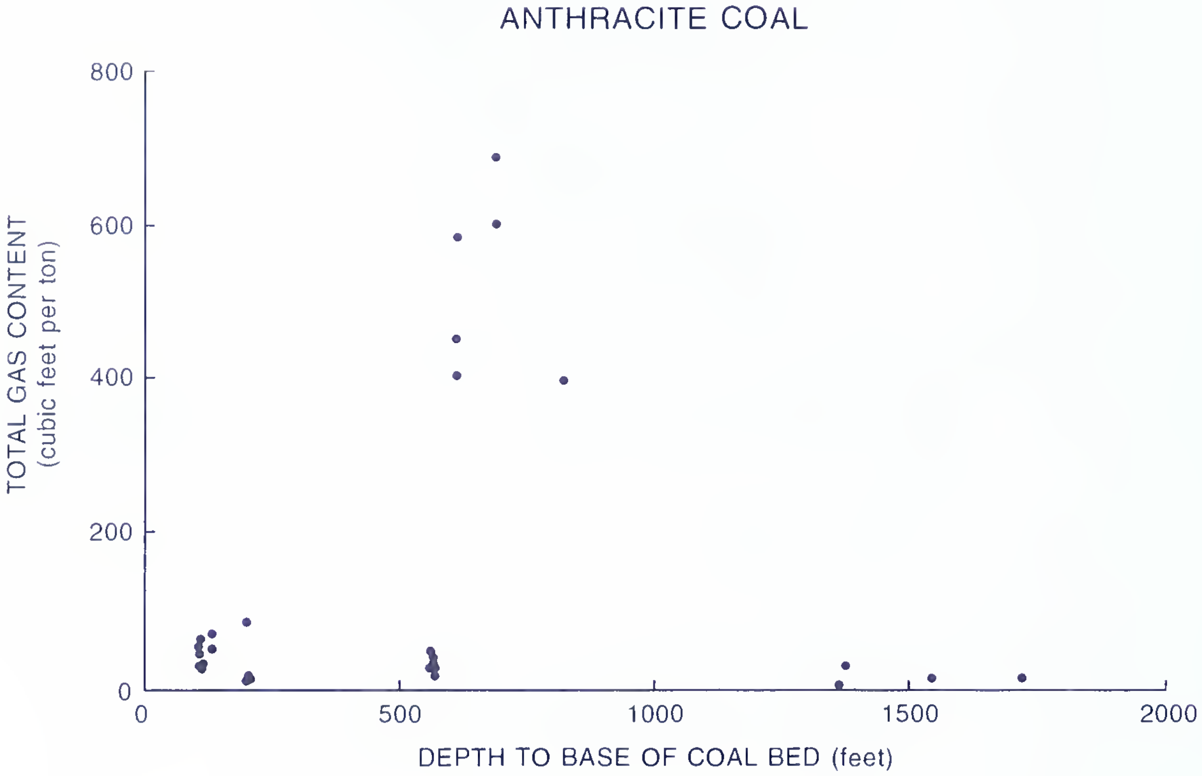

HIGH-VOLATILE A BITUMINOUS COAL

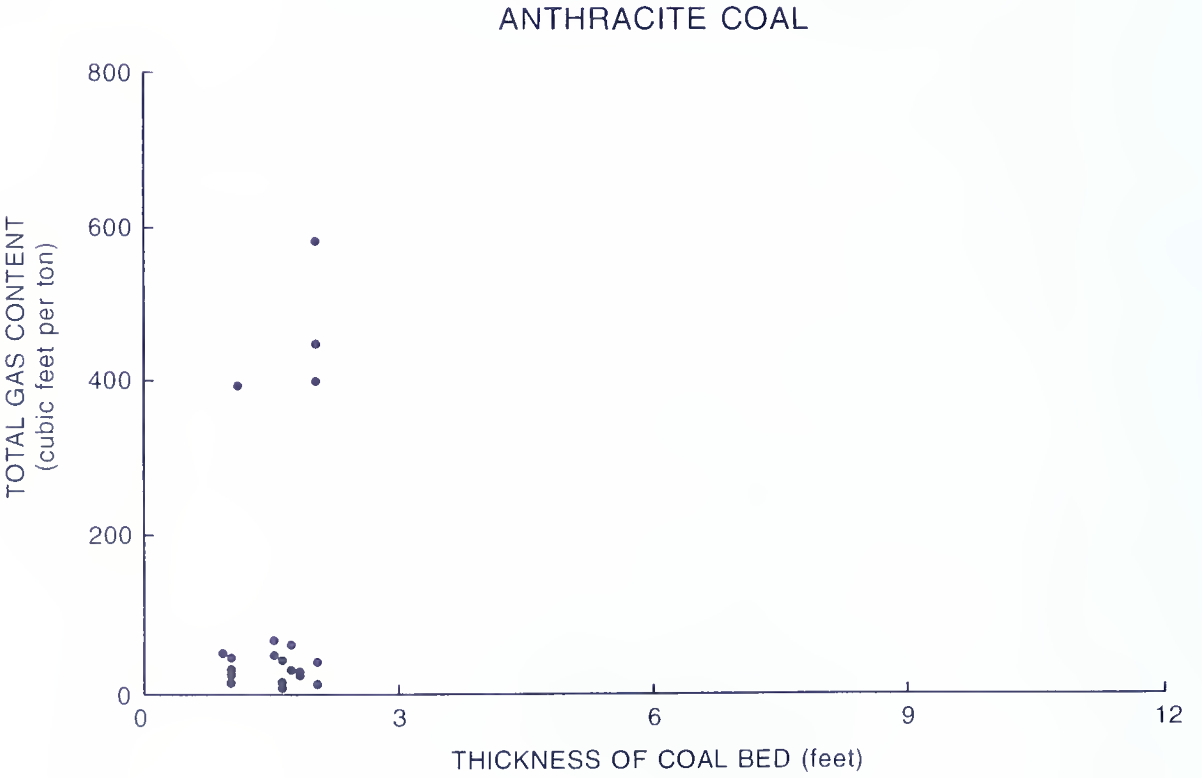

MEDIUM-VOLATILE BITUMINOUS COAL
TOTAL GAS CONTENT (cubic feet per ton)
0
200
400
600
800
0
500
1000
1500
2000
DEPTH TO BASE OF COAL BED (feet)

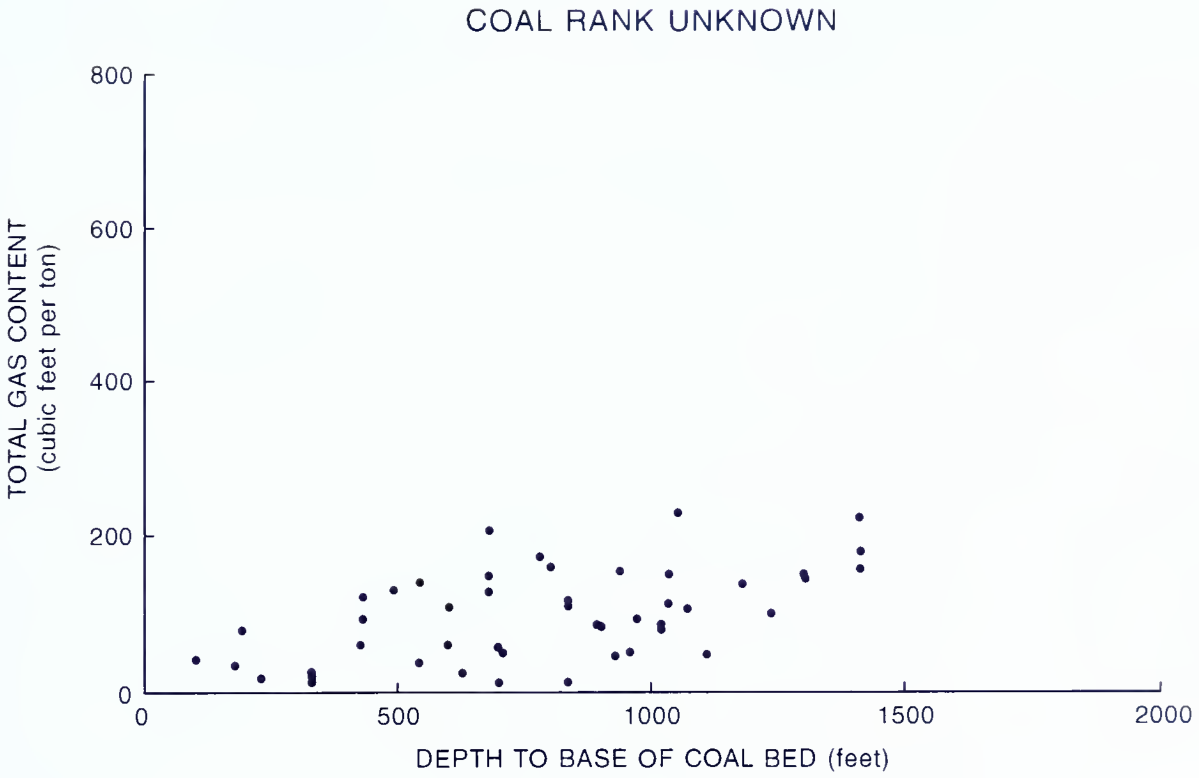

MEDIUM-VOLATILE BITUMINOUS COAL
TOTAL GAS CONTENT (cubic feet per ton)
0
200
400
600
800
0
3
6
9
12
THICKNESS OF COAL BED (feet)

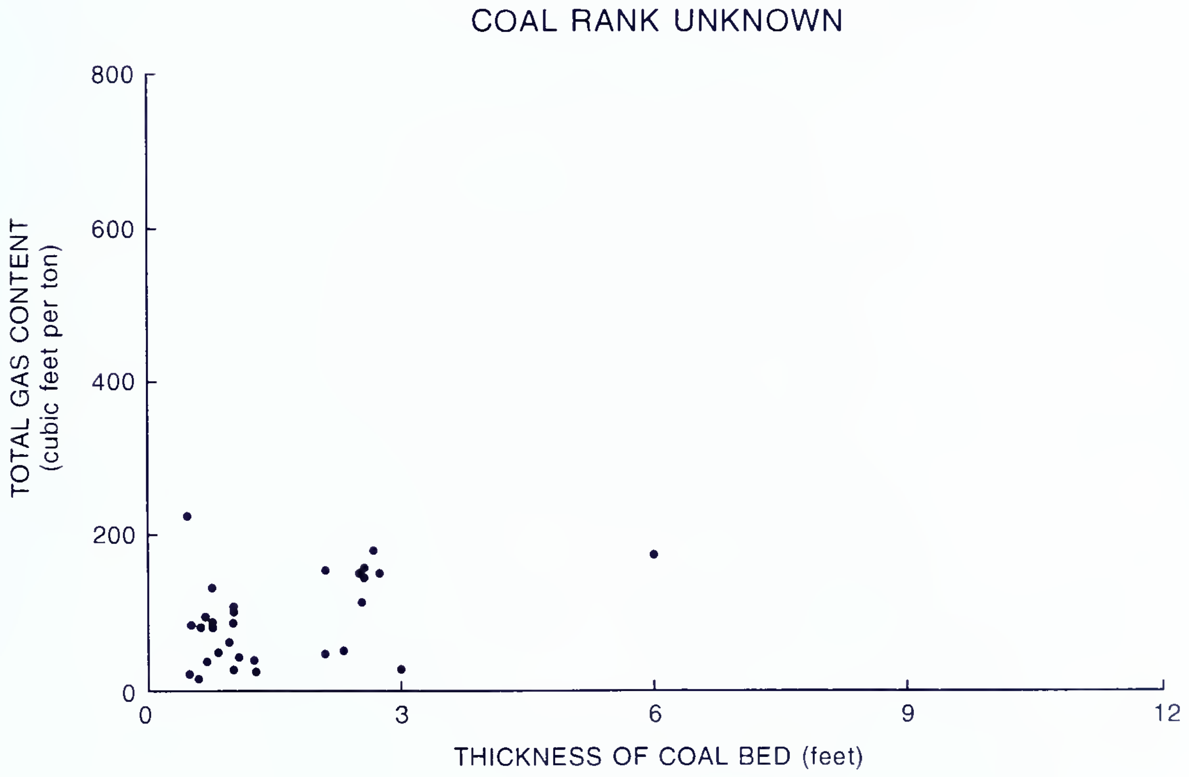

LOW-VOLATILE BITUMINOUS COAL
TOTAL GAS CONTENT
(cubic feet per ton)
800
600
400
200
0
0
500
1000
1500
2000
DEPTH TO BASE OF COAL BED (feet)


LOW-VOLATILE BITUMINOUS COAL
TOTAL GAS CONTENT
(cubic feet per ton)
800
600
400
200
0
0
3
6
9
12
THICKNESS OF COAL BED (feet)


ANTHRACITE COAL
TOTAL GAS CONTENT (cubic feet per ton)
800
600
400
200
0
0
500
1000
1500
2000
DEPTH TO BASE OF COAL BED (feet)


ANTHRACITE COAL
TOTAL GAS CONTENT (cubic feet per ton)
800
600
400
200
0
0
3
6
9
12
THICKNESS OF COAL BED (feet)

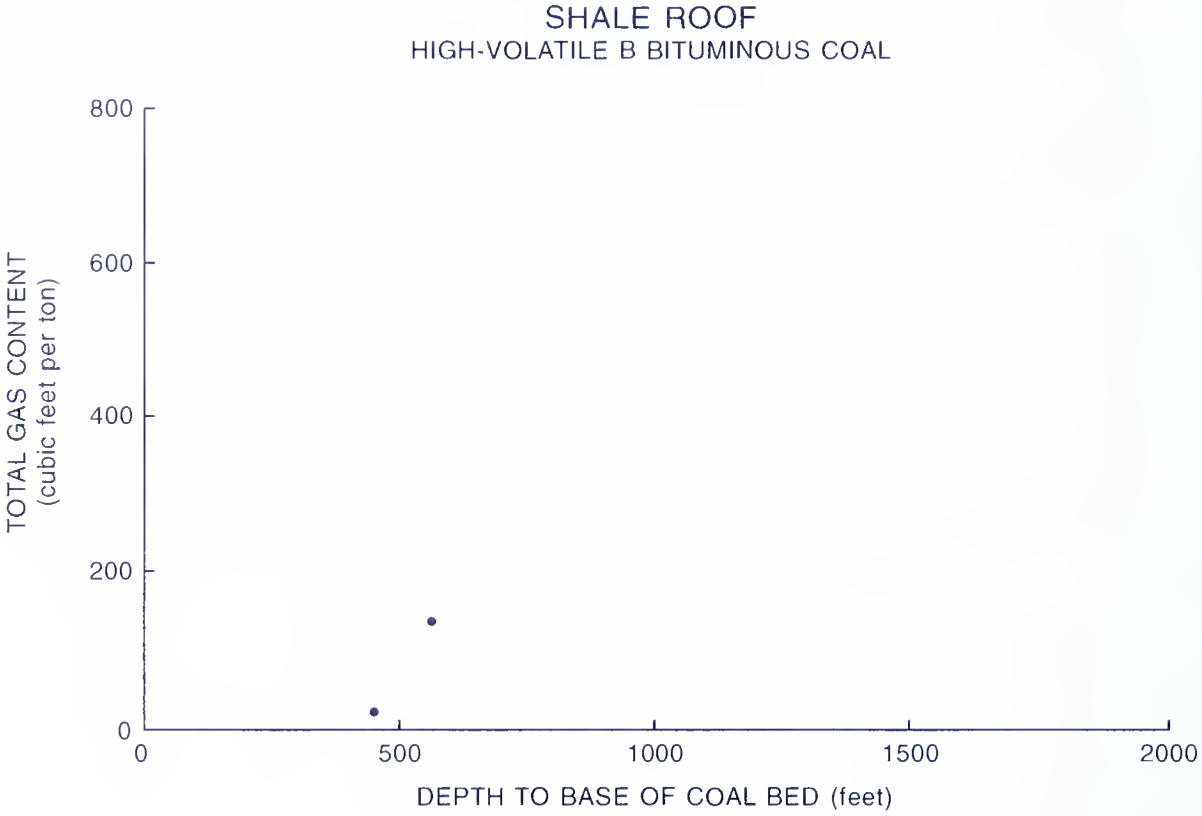

COAL RANK UNKNOWN
TOTAL GAS CONTENT
(cubic feet per ton)
800
600
400
200
0
0
500
1000
1500
2000
DEPTH TO BASE OF COAL BED (feet)

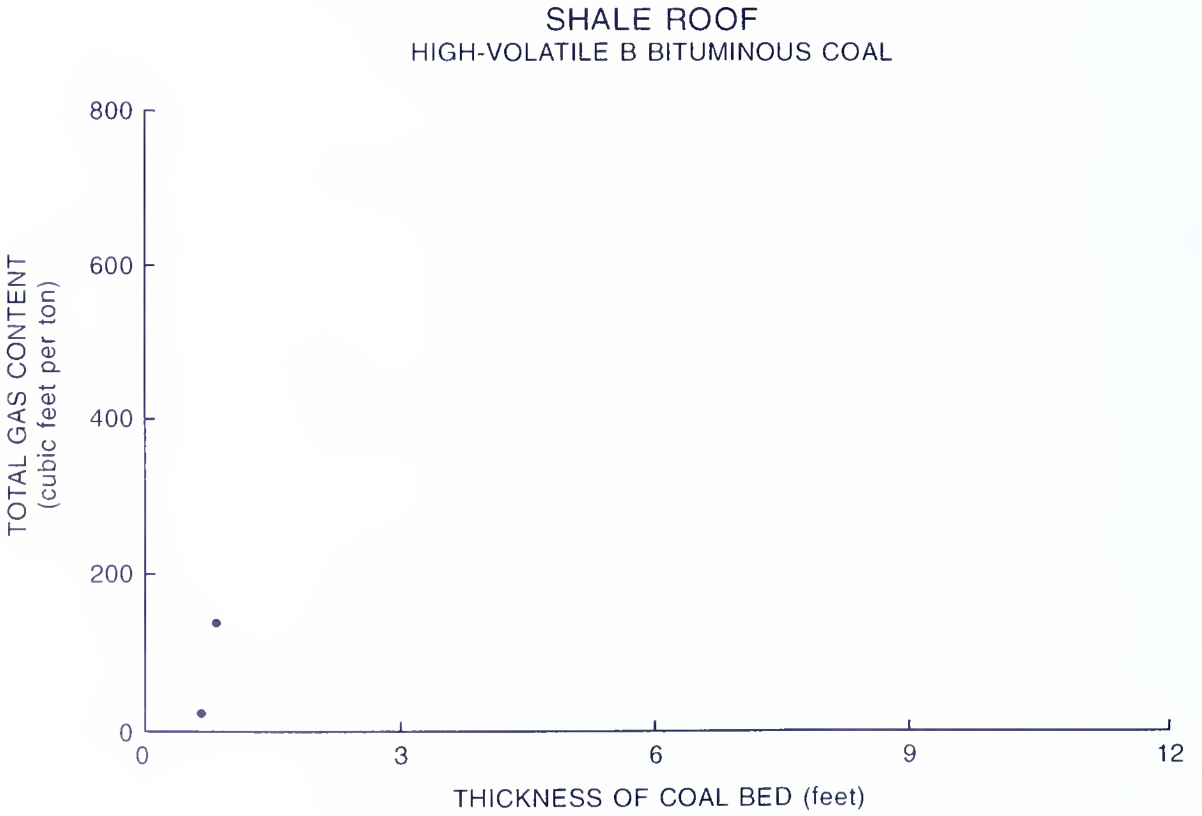

COAL RANK UNKNOWN
TOTAL GAS CONTENT
(cubic feet per ton)
800
600
400
200
0
0
3
6
9
12
THICKNESS OF COAL BED (feet)

APPENDIX 5

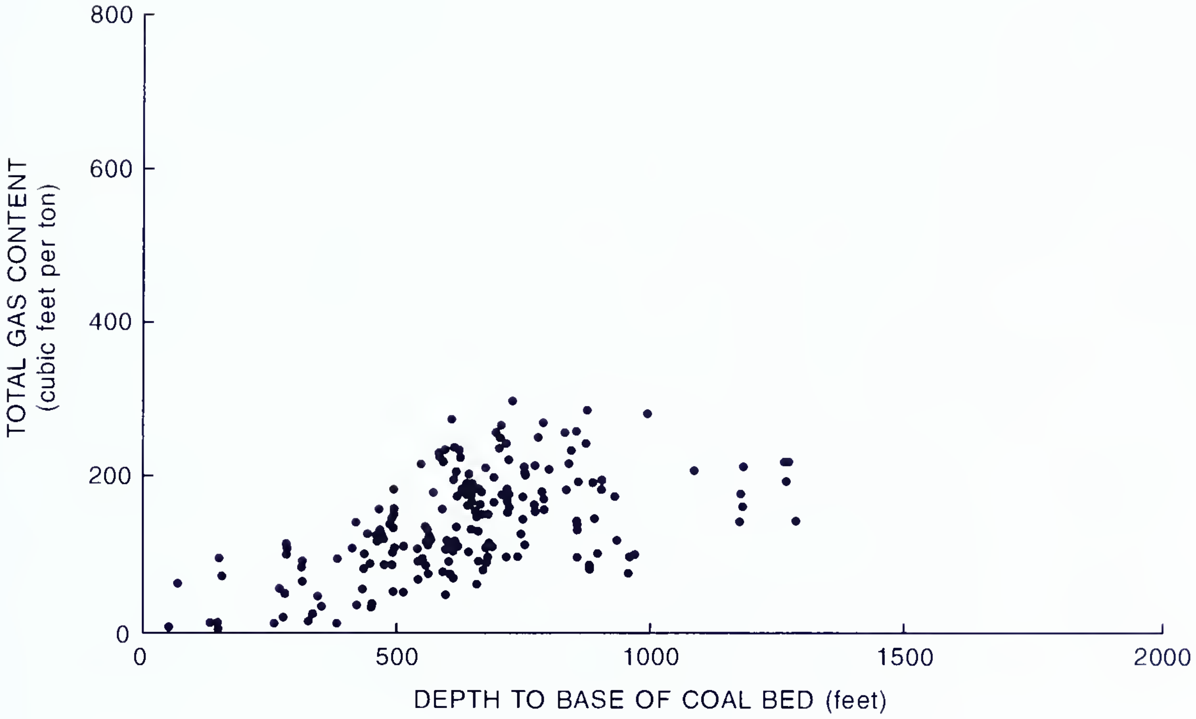
GAS CONTENT BASED ON COAL RANK AND ROOF LITHOLOGY

Appendix 5 contains graphs of total gas content versus depth to the base of the coal bed and total gas content versus the thickness of the coal bed based on both rank and roof lithology of the coal beds (both bituminous and anthracite) (some data from Diamond, LaScola, and Hyman, 1986, and U.S. Bureau of Mines, 1990).

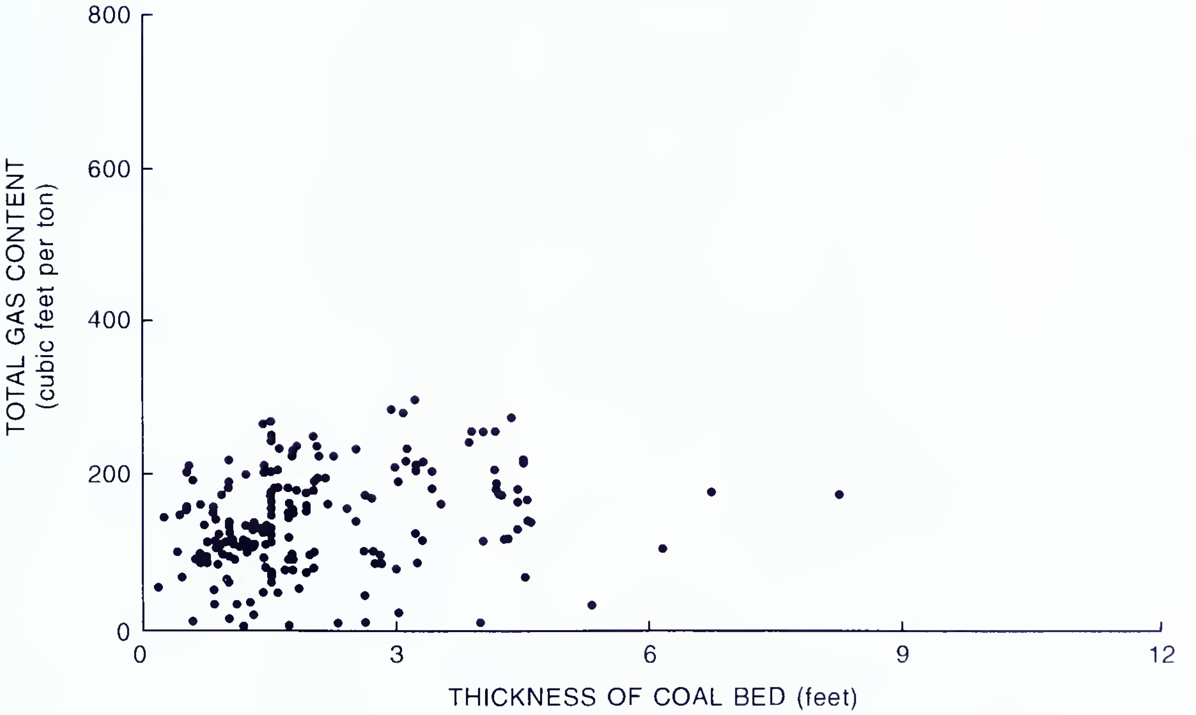


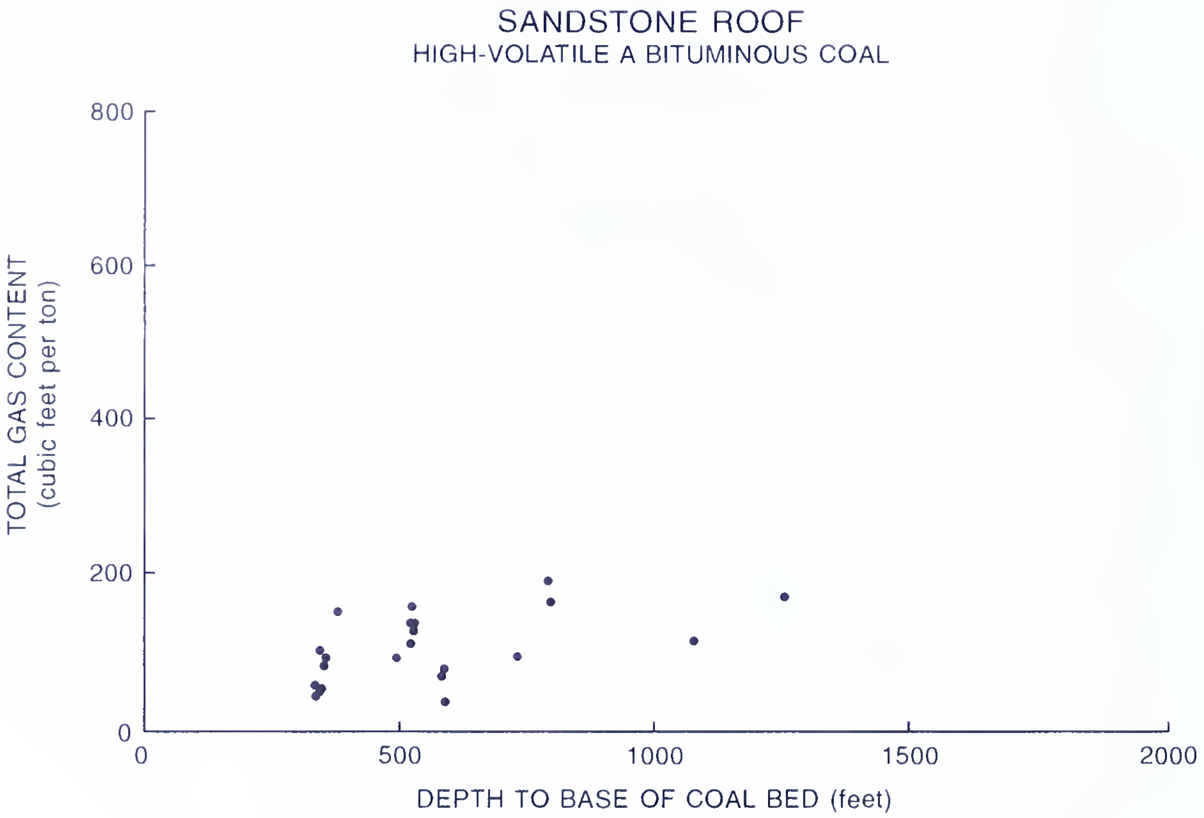


SHALE ROOF
HIGH-VOLATILE A BITUMINOUS COAL

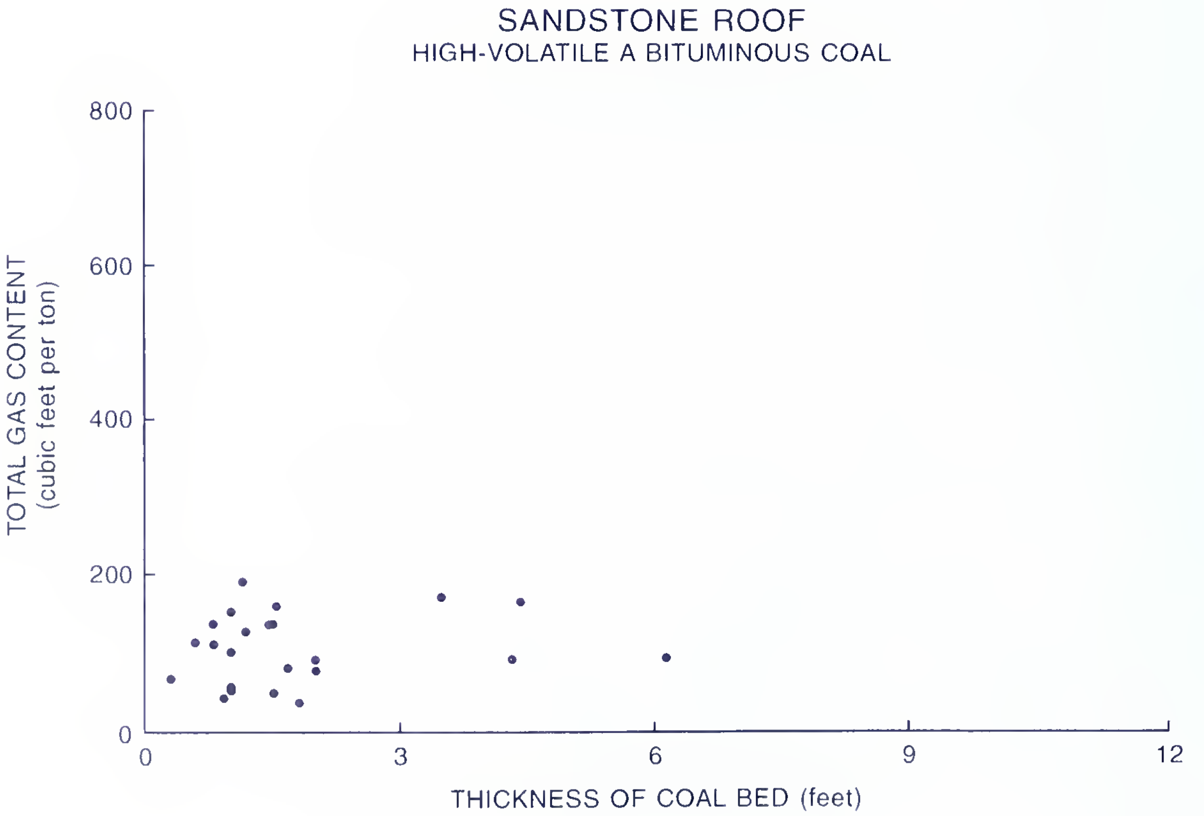


SHALE ROOF
HIGH-VOLATILE A BITUMINOUS COAL

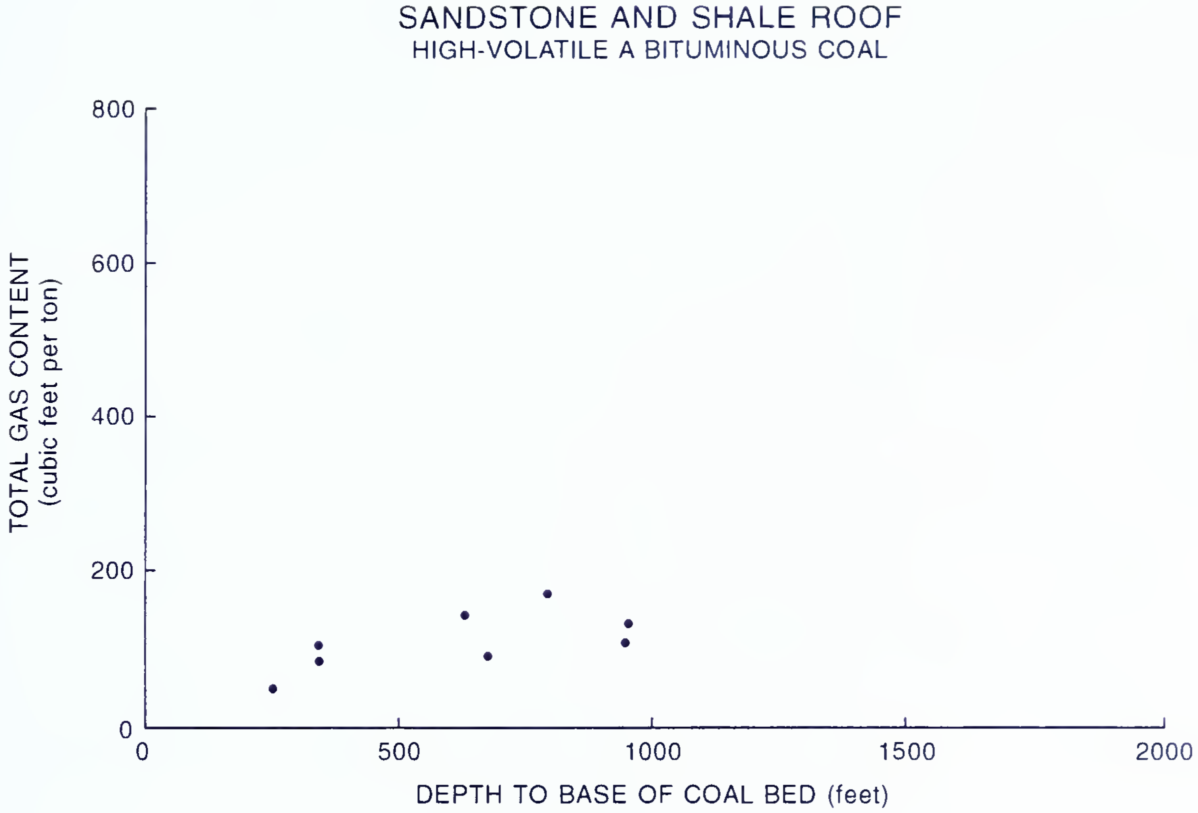


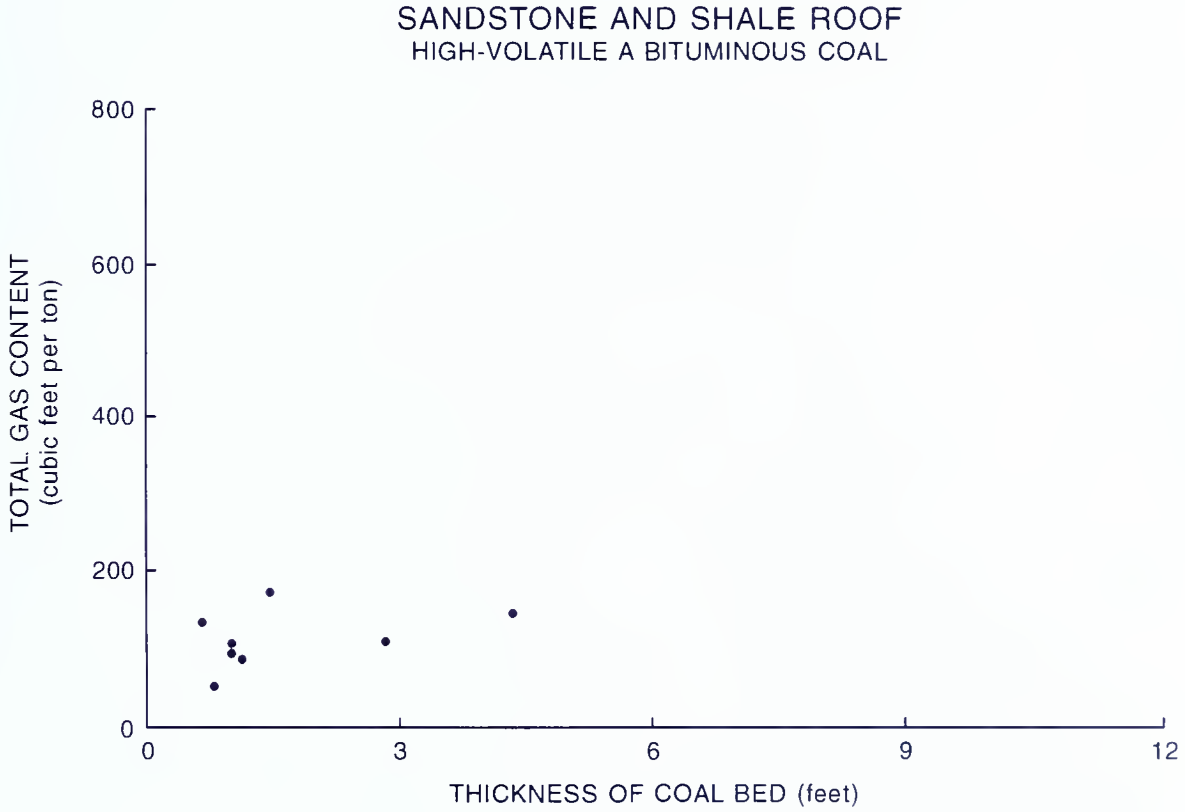


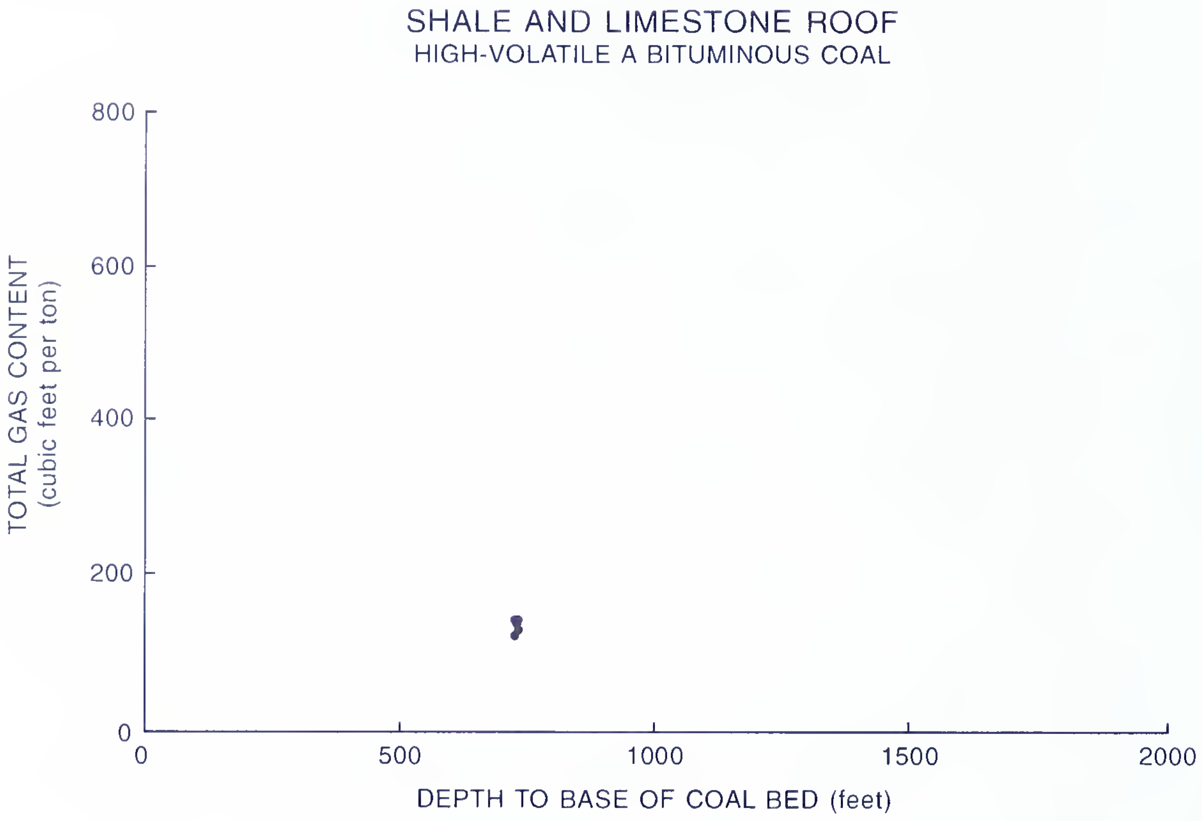
SANDSTONE ROOF
HIGH-VOLATILE A BITUMINOUS COAL



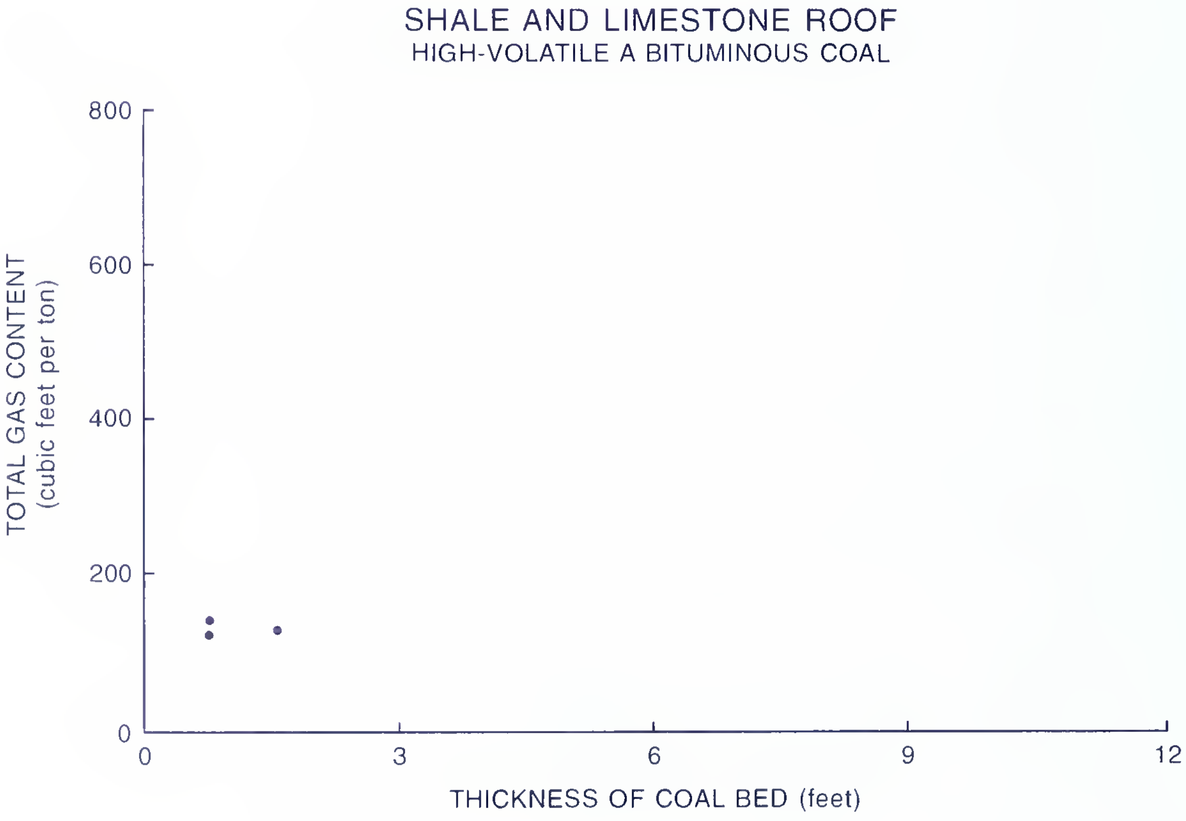
SANDSTONE ROOF
HIGH-VOLATILE A BITUMINOUS COAL


SANDSTONE AND SHALE ROOF
HIGH-VOLATILE A BITUMINOUS COAL

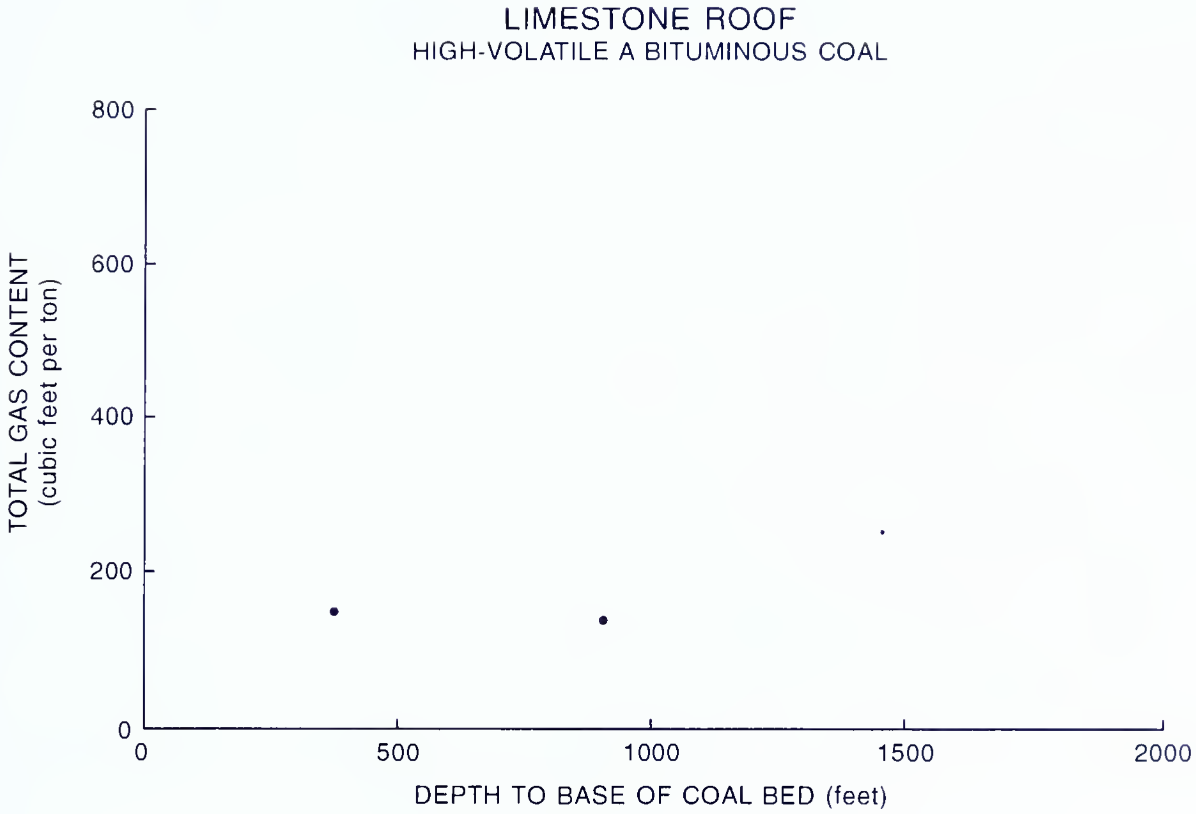

SANDSTONE AND SHALE ROOF
HIGH-VOLATILE A BITUMINOUS COAL

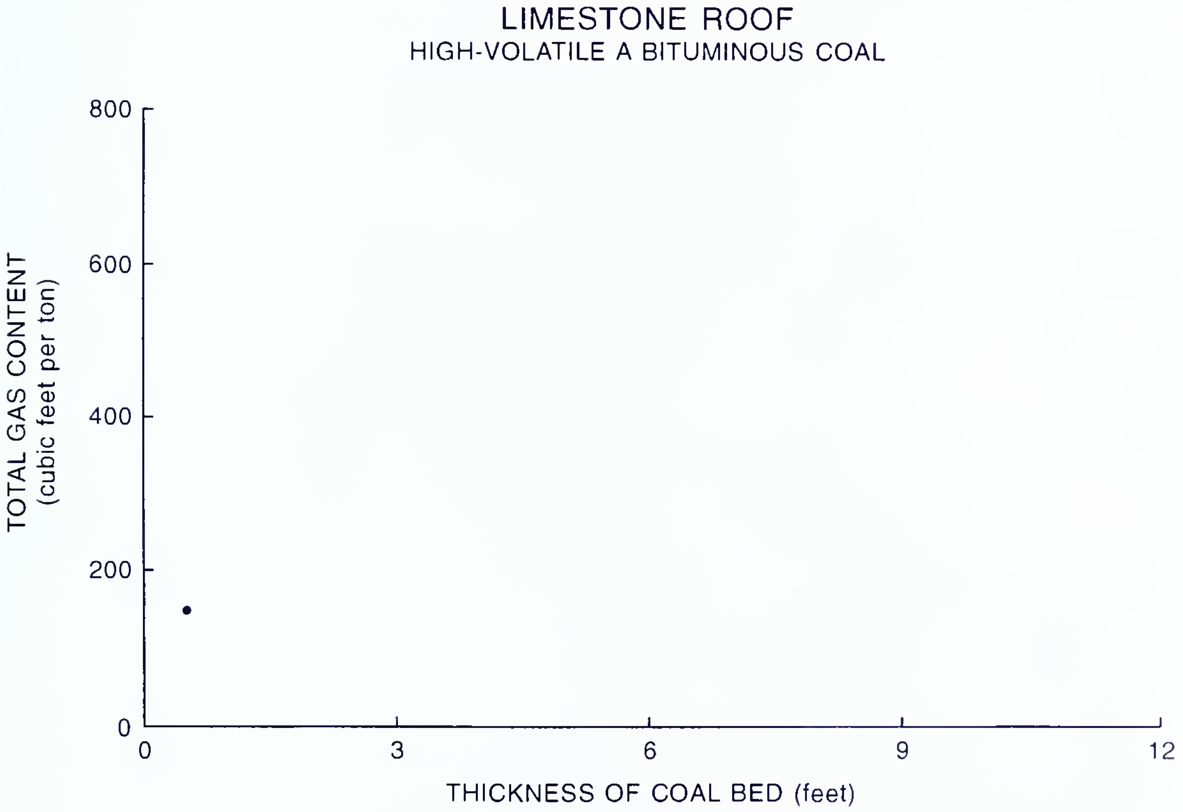


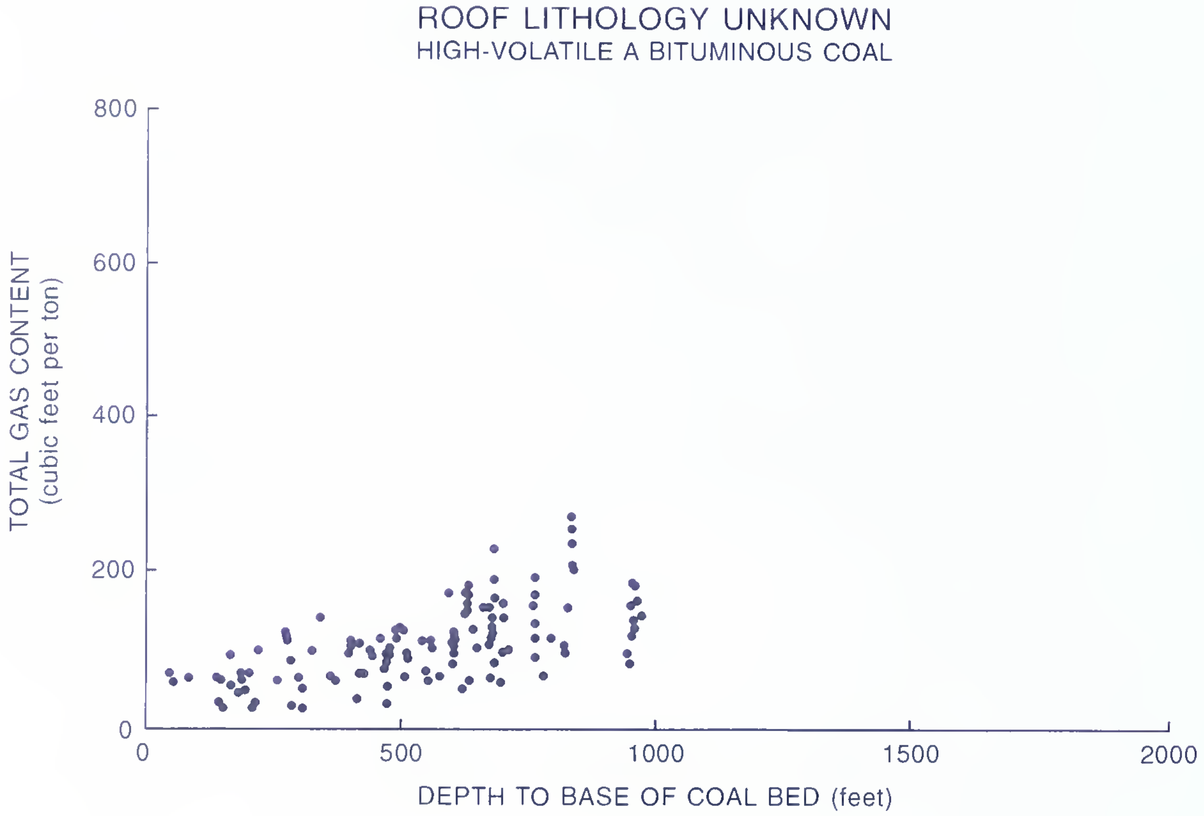
SHALE AND LIMESTONE ROOF
HIGH-VOLATILE A BITUMINOUS COAL

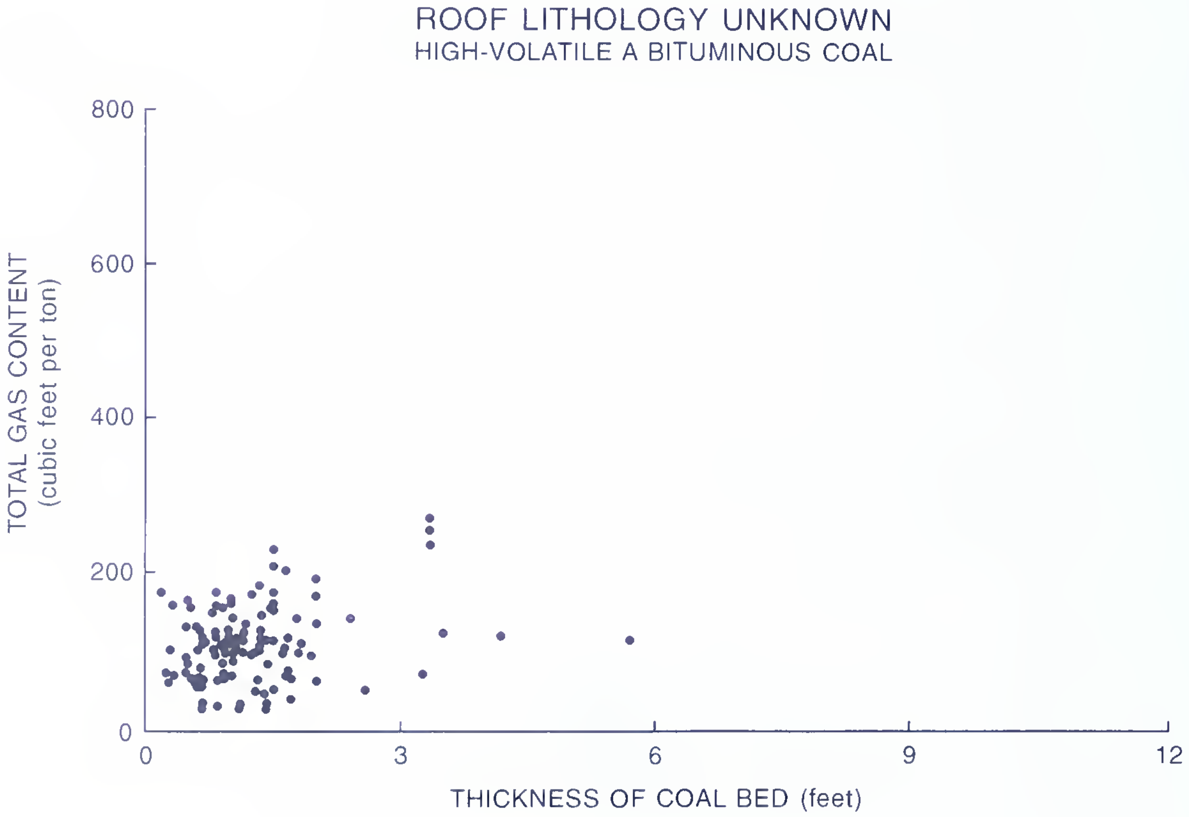


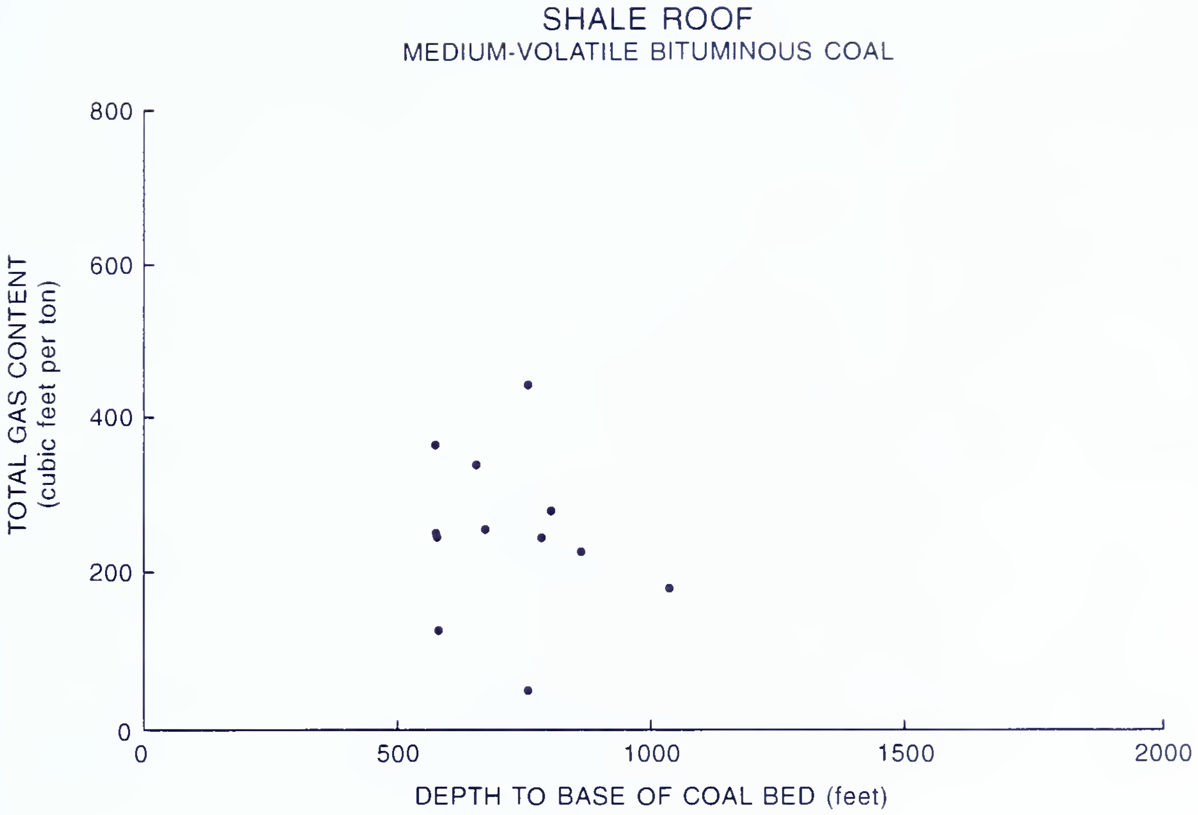
SHALE AND LIMESTONE ROOF
HIGH-VOLATILE A BITUMINOUS COAL

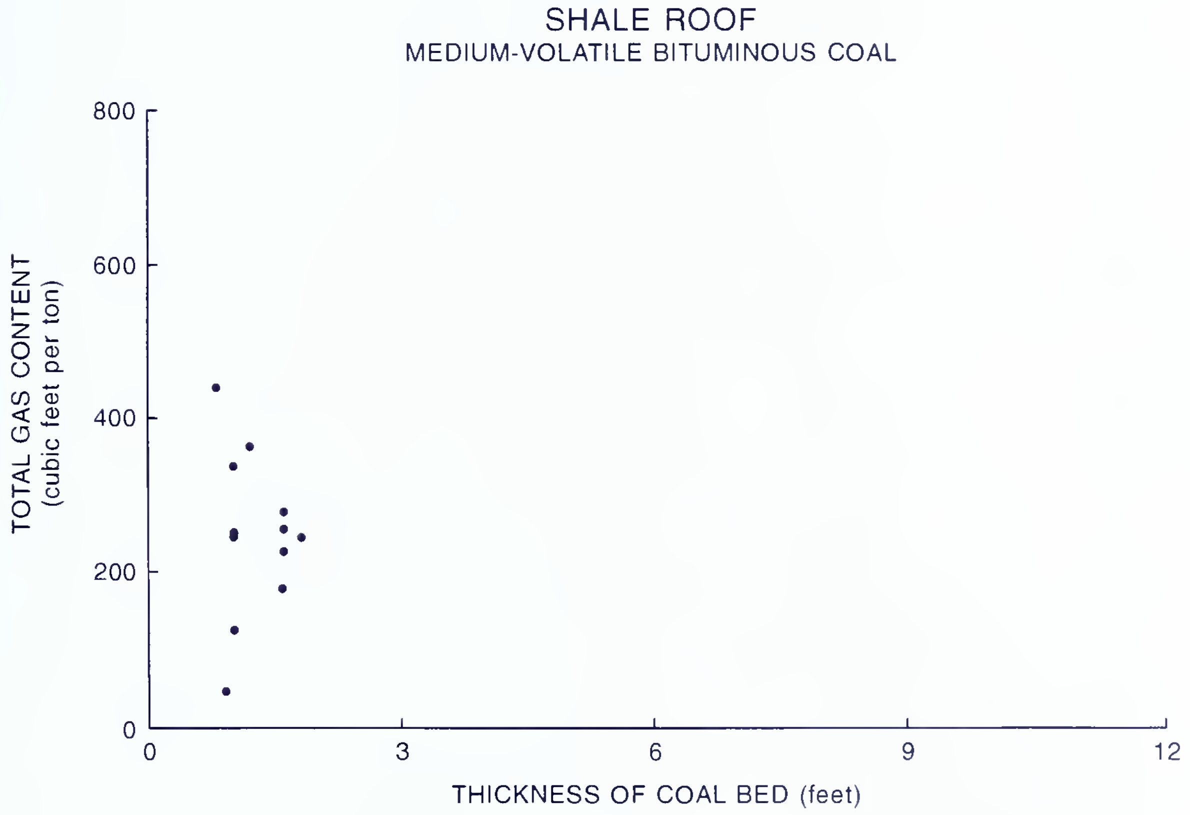

LIMESTONE ROOF
HIGH-VOLATILE A BITUMINOUS COAL
TOTAL GAS CONTENT
(cubic feet per ton)
800
600
400
200
0
0
500
1000
1500
2000
DEPTH TO BASE OF COAL BED (feet)

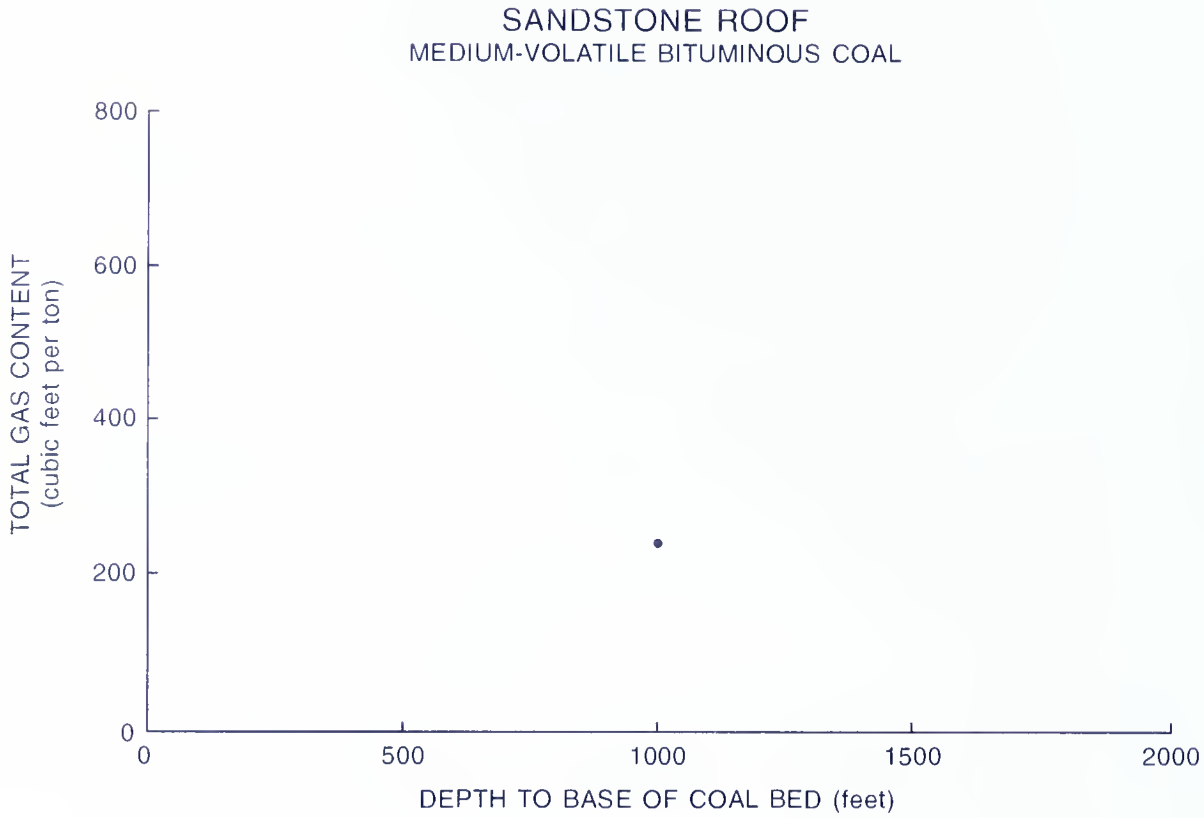

LIMESTONE ROOF
HIGH-VOLATILE A BITUMINOUS COAL
TOTAL GAS CONTENT
(cubic feet per ton)
800
600
400
200
0
0
3
6
9
12
THICKNESS OF COAL BED (feet)

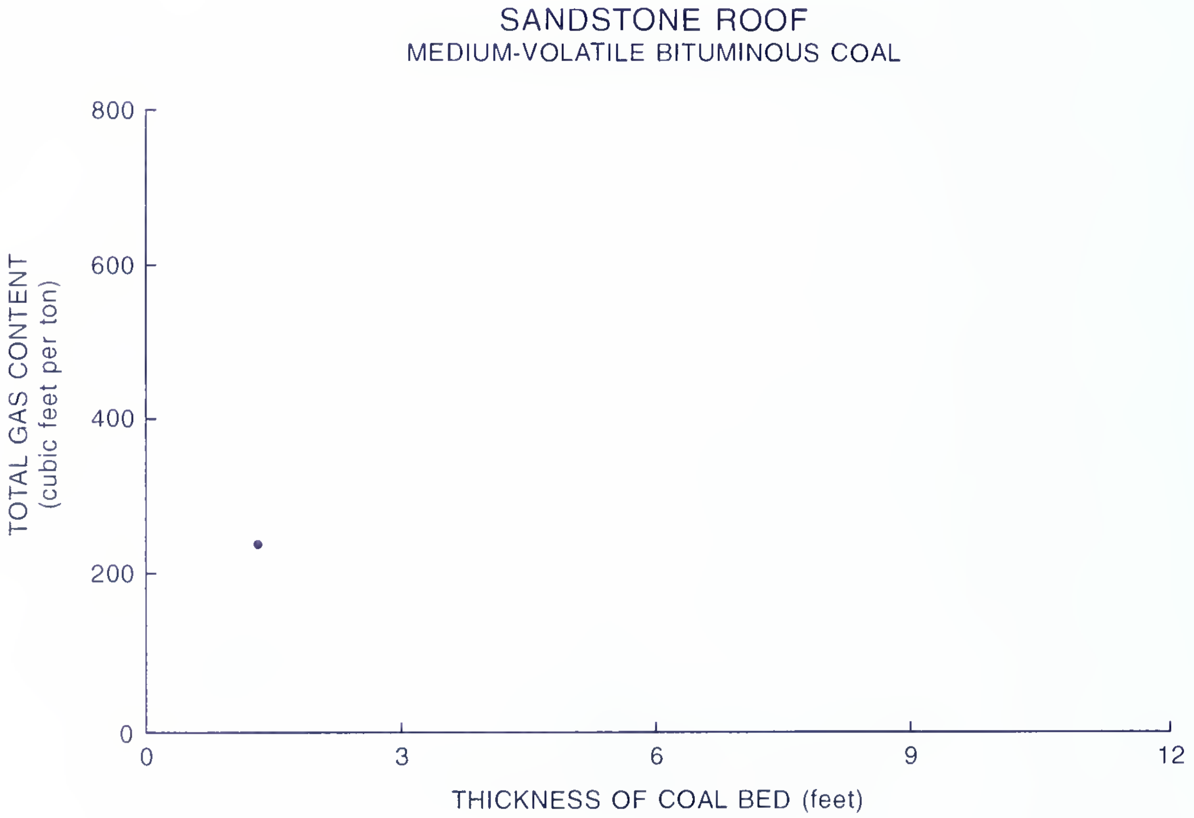

ROOF LITHOLOGY UNKNOWN
HIGH-VOLATILE A BITUMINOUS COAL
TOTAL GAS CONTENT
(cubic feet per ton)
800
600
400
200
0
0
500
1000
1500
2000
DEPTH TO BASE OF COAL BED (feet)


ROOF LITHOLOGY UNKNOWN
HIGH-VOLATILE A BITUMINOUS COAL
TOTAL GAS CONTENT
(cubic feet per ton)
800
600
400
200
0
0
3
6
9
12
THICKNESS OF COAL BED (feet)

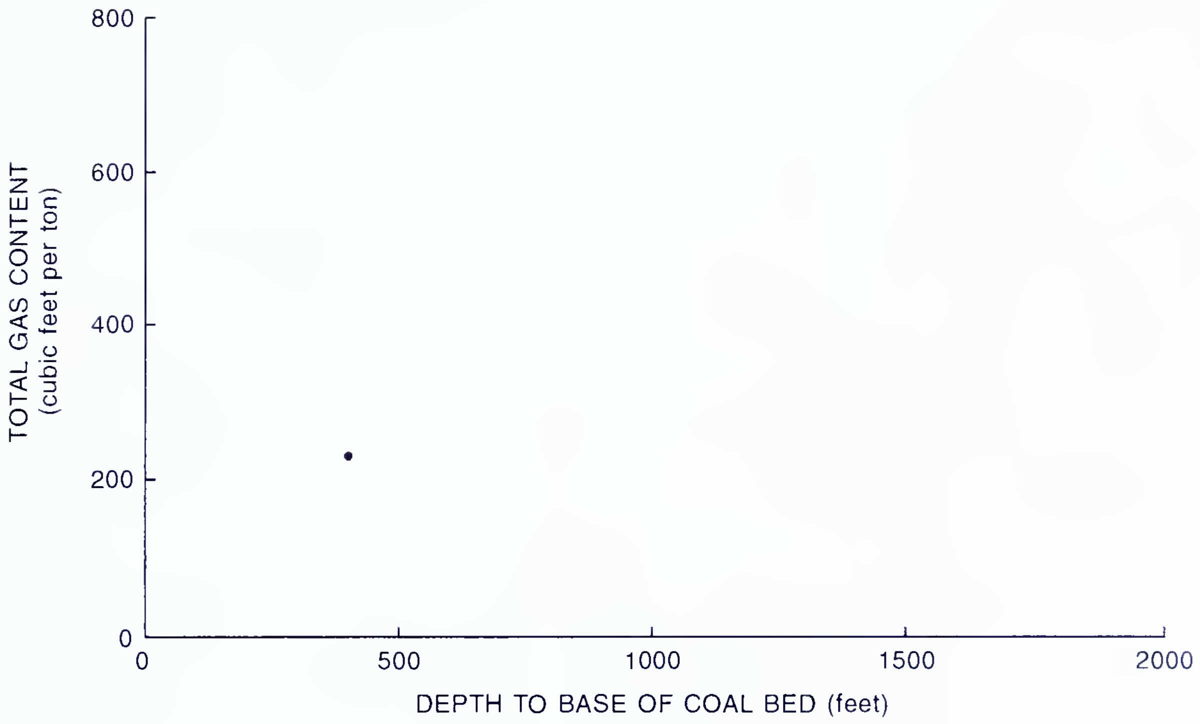

SHALE ROOF
MEDIUM-VOLATILE BITUMINOUS COAL
TOTAL GAS CONTENT (cubic feet per ton)
800
600
400
200
0
0
500
1000
1500
2000
DEPTH TO BASE OF COAL BED (feet)


SHALE ROOF
MEDIUM-VOLATILE BITUMINOUS COAL
TOTAL GAS CONTENT (cubic feet per ton)
800
600
400
200
0
0
3
6
9
12
THICKNESS OF COAL BED (feet)

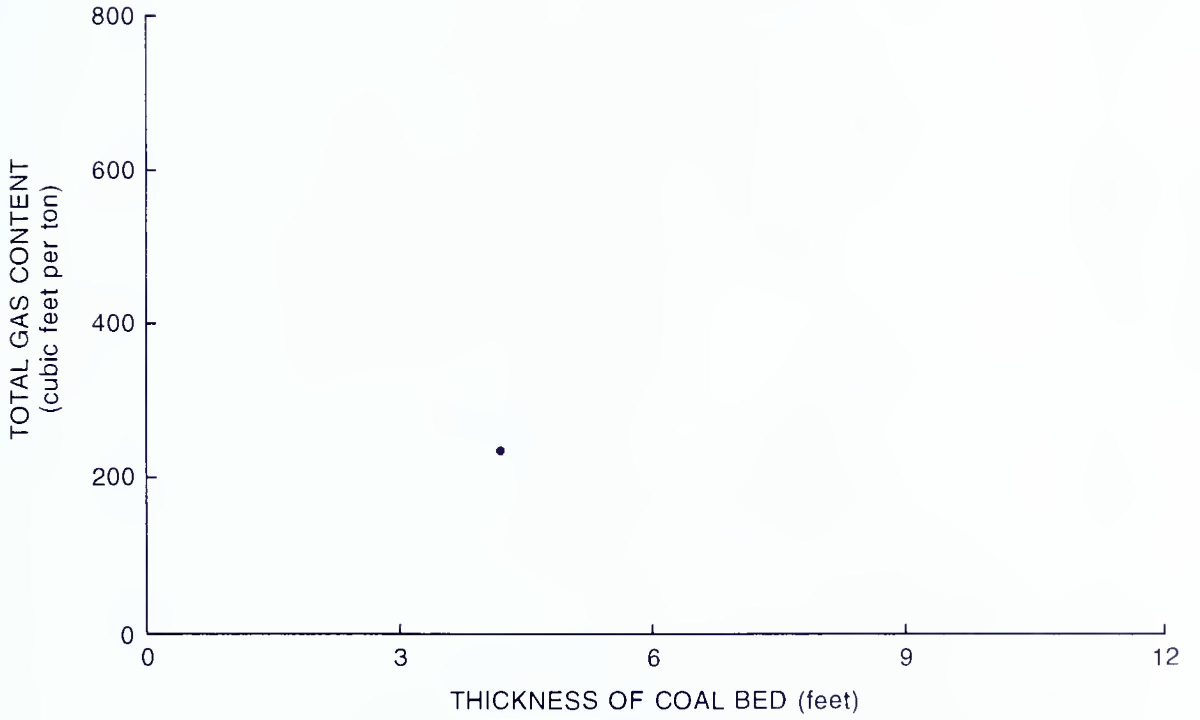

SANDSTONE ROOF
MEDIUM-VOLATILE BITUMINOUS COAL

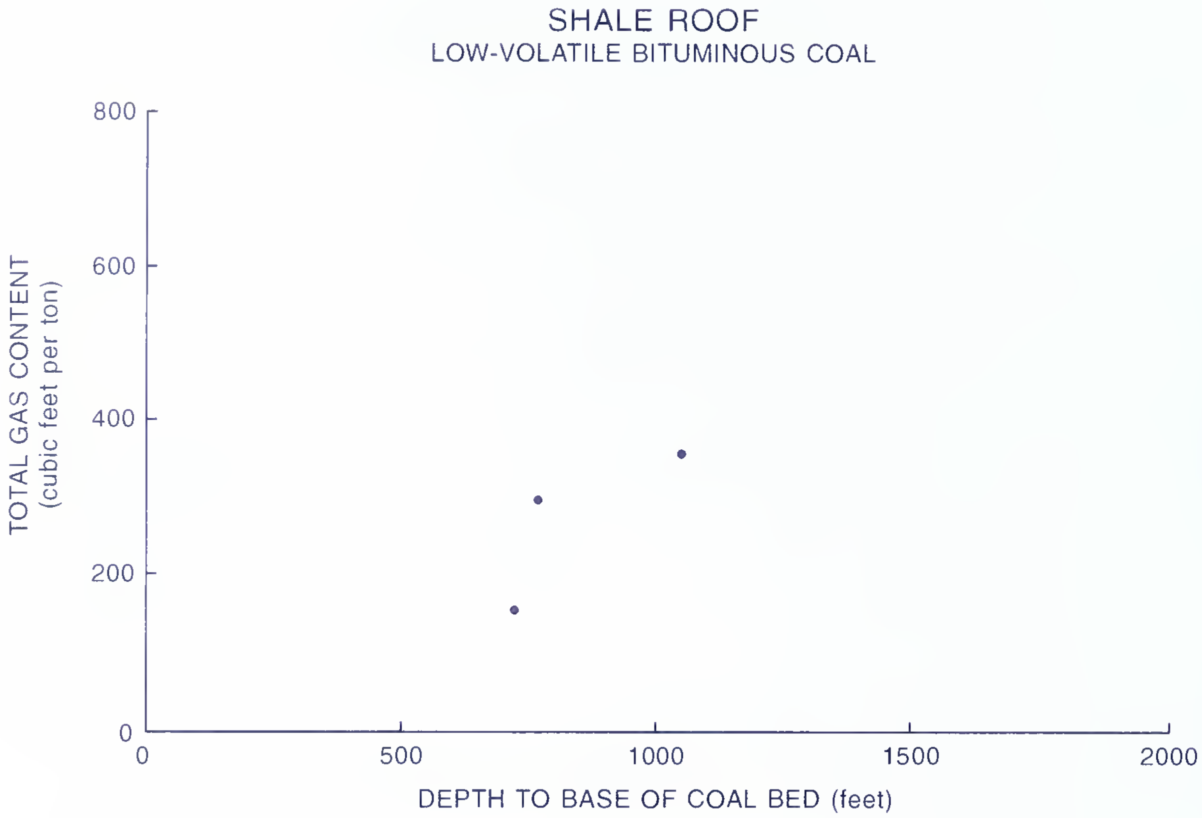

SANDSTONE ROOF
MEDIUM-VOLATILE BITUMINOUS COAL

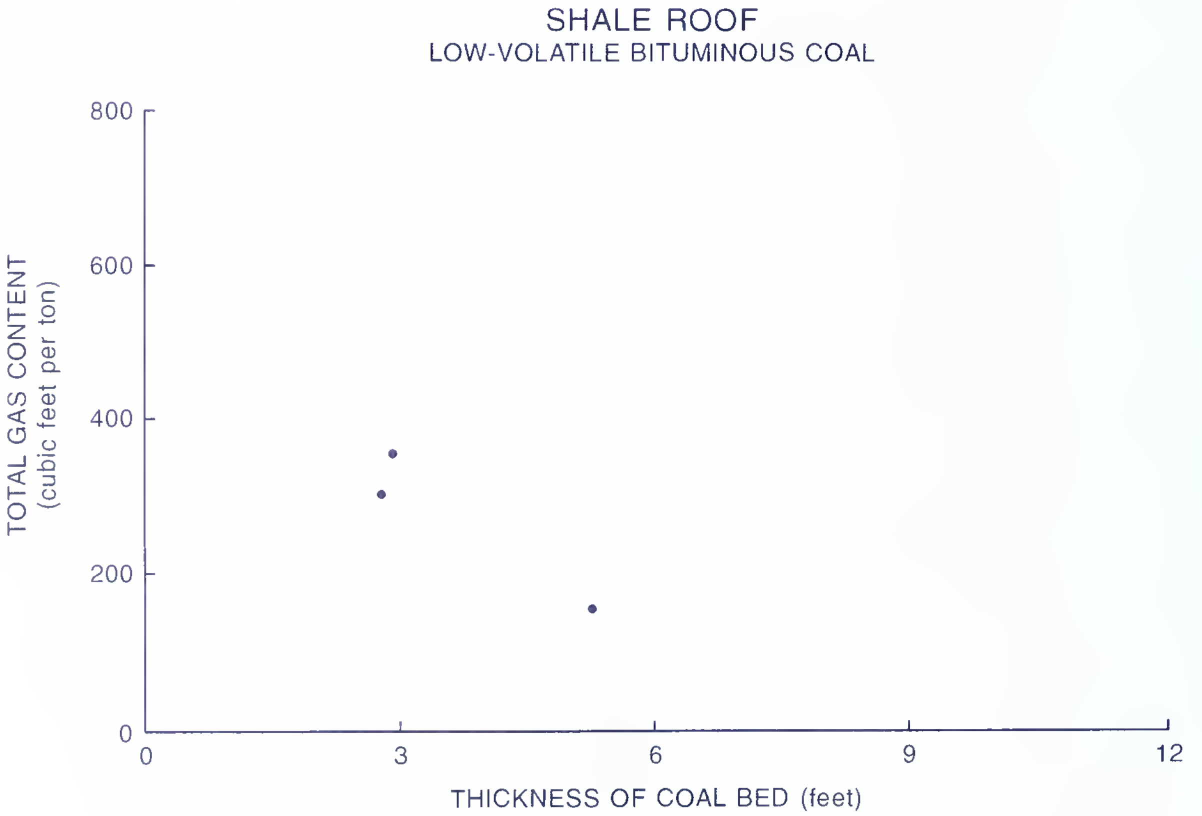
ROOF LITHOLOGY UNKNOWN
MEDIUM-VOLATILE BITUMINOUS COAL

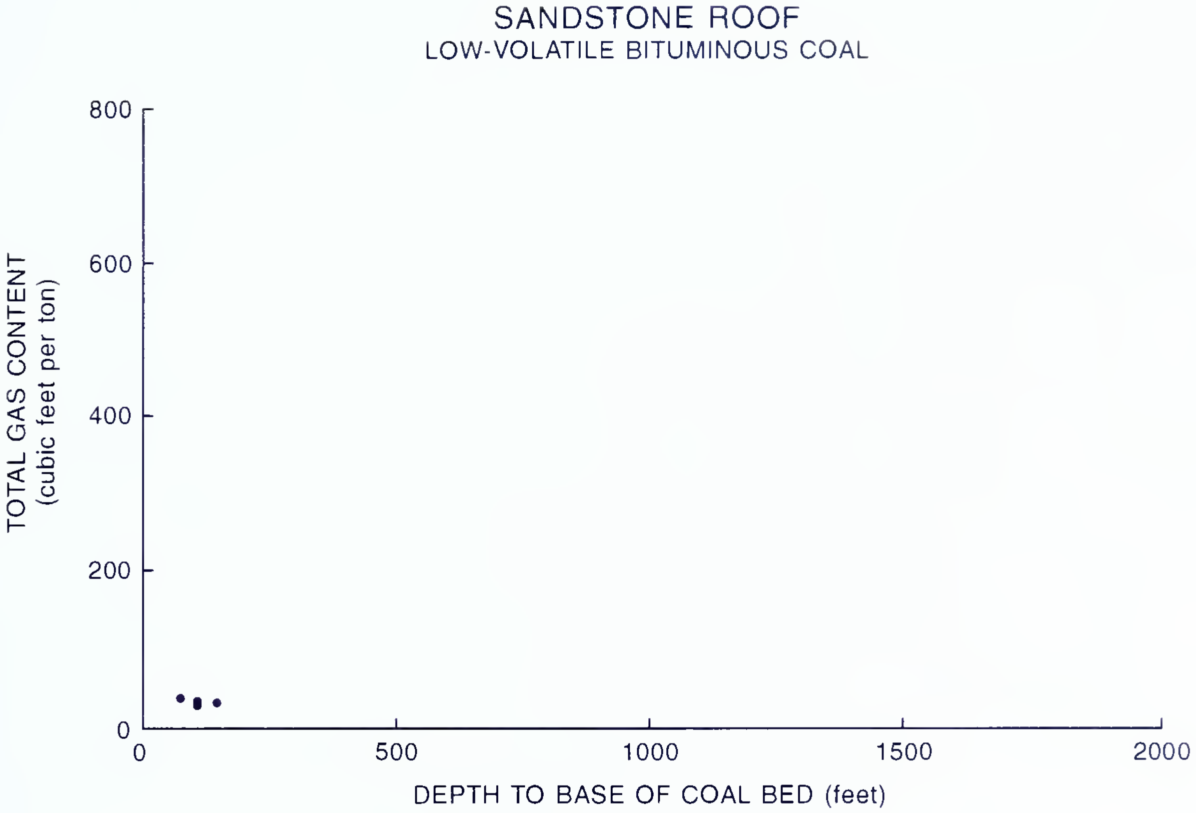


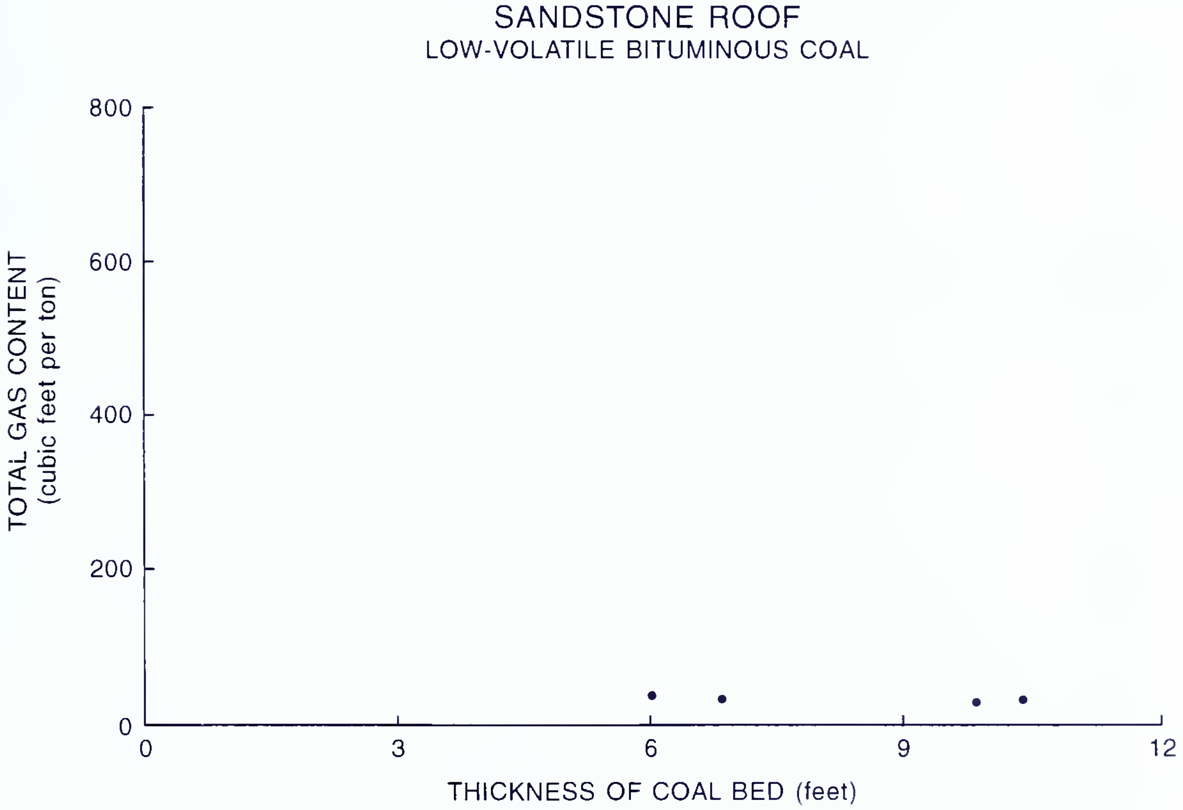
ROOF LITHOLOGY UNKNOWN
MEDIUM-VOLATILE BITUMINOUS COAL

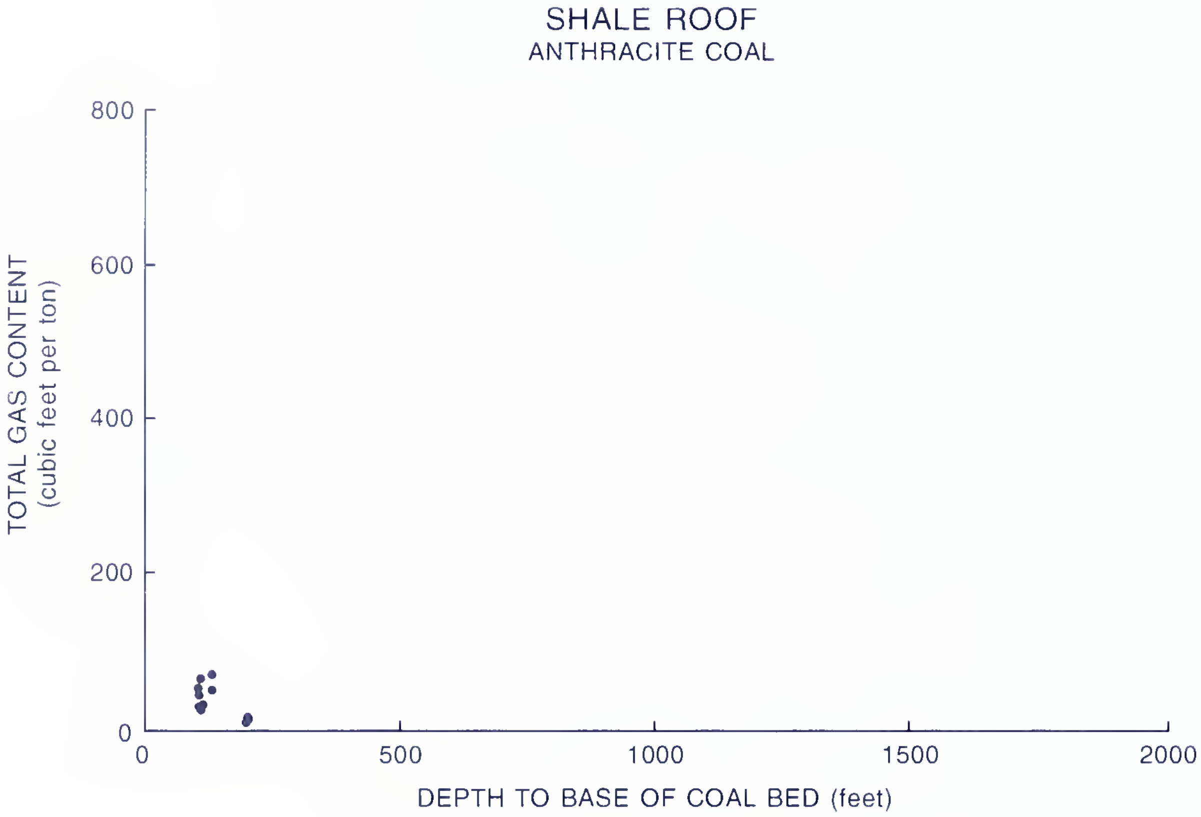


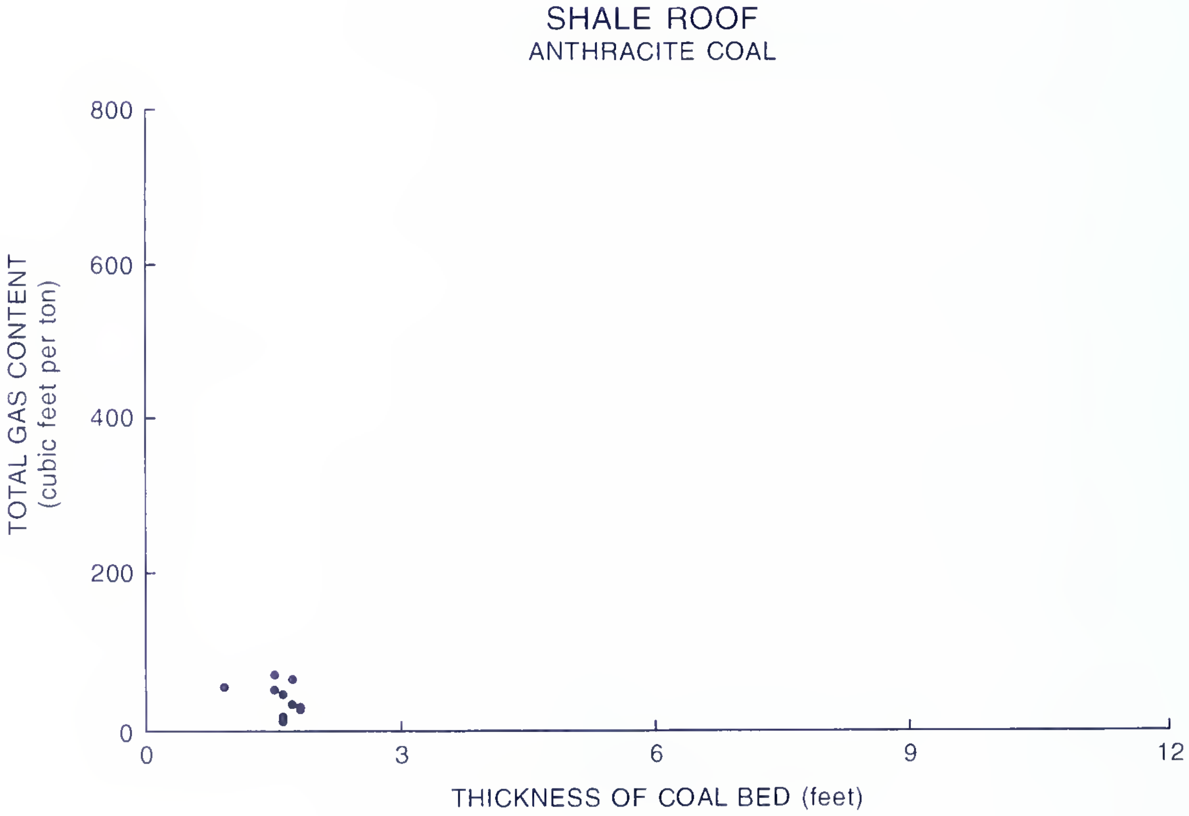

SHALE ROOF
LOW-VOLATILE BITUMINOUS COAL
TOTAL GAS CONTENT (cubic feet per ton)
0
200
400
600
800
0
500
1000
1500
2000
DEPTH TO BASE OF COAL BED (feet)

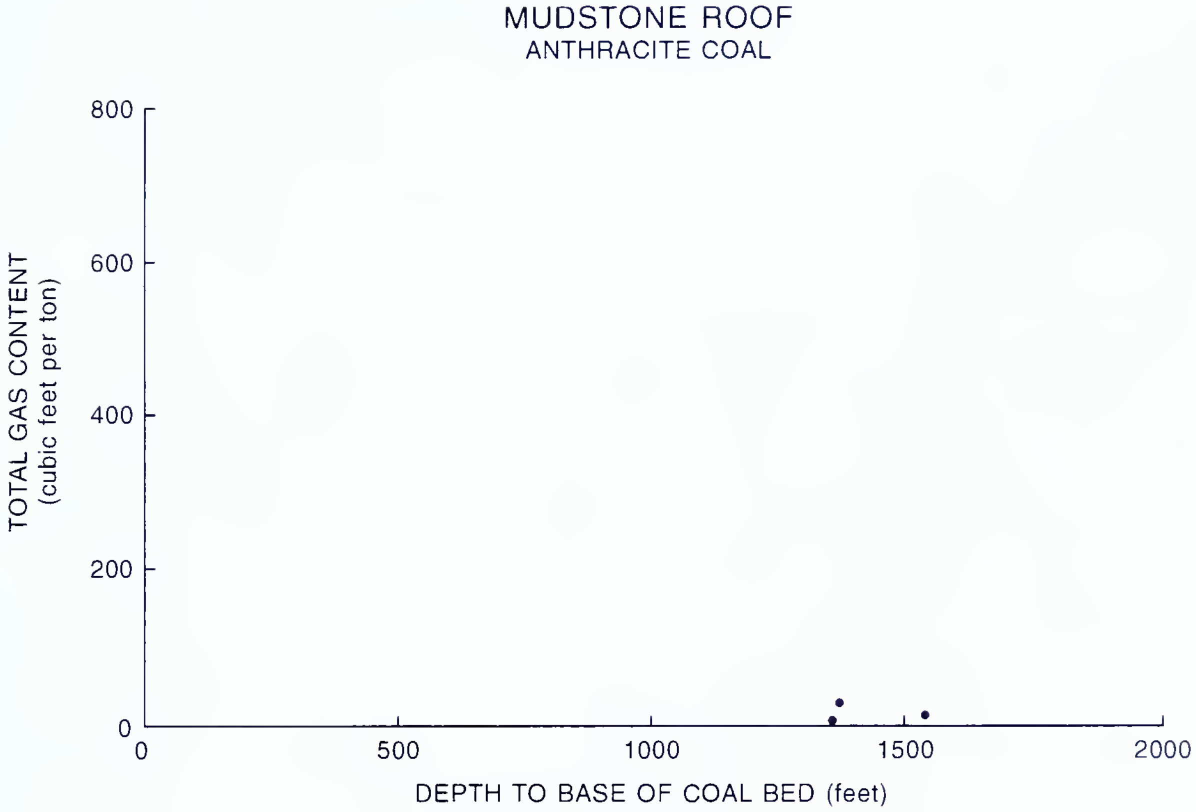

SHALE ROOF
LOW-VOLATILE BITUMINOUS COAL
TOTAL GAS CONTENT (cubic feet per ton)
0
200
400
600
800
0
3
6
9
12
THICKNESS OF COAL BED (feet)


SANDSTONE ROOF
LOW-VOLATILE BITUMINOUS COAL
TOTAL GAS CONTENT (cubic feet per ton)
800
600
400
200
0
0
500
1000
1500
2000
DEPTH TO BASE OF COAL BED (feet)

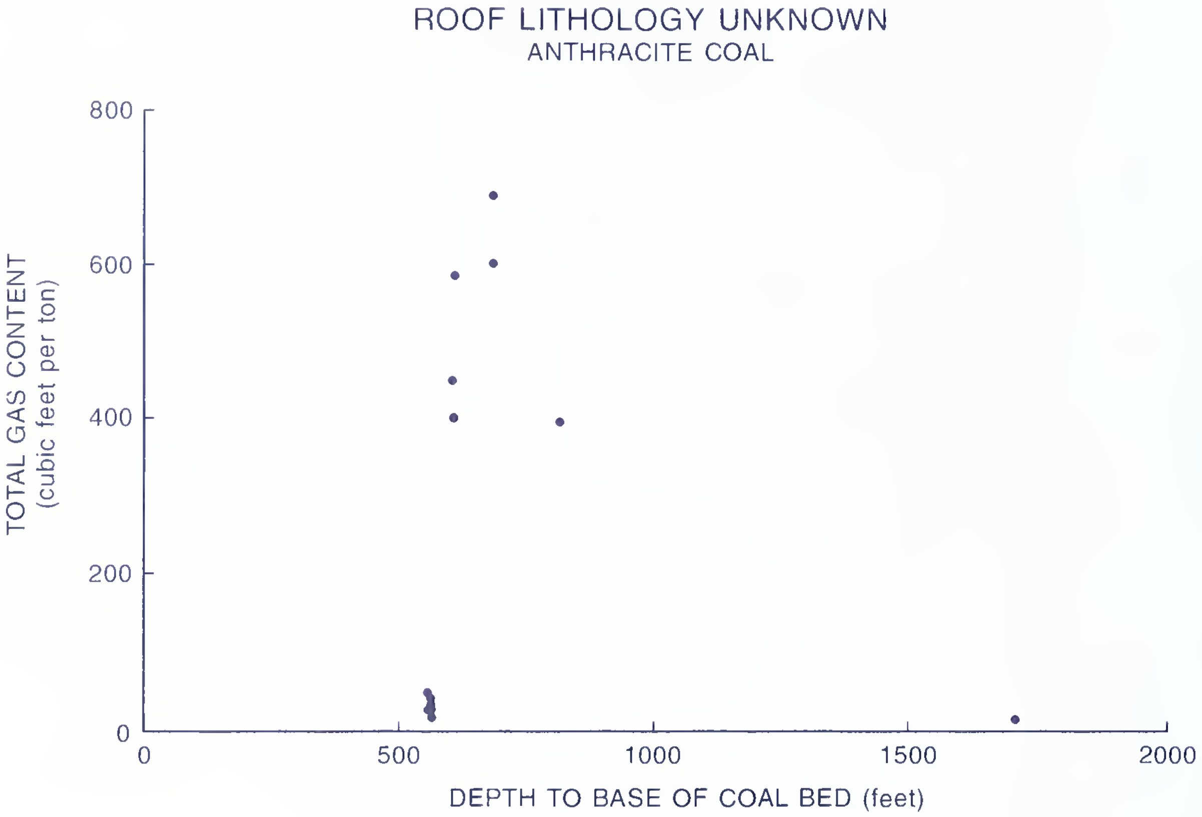

SANDSTONE ROOF
LOW-VOLATILE BITUMINOUS COAL
TOTAL GAS CONTENT (cubic feet per ton)
800
600
400
200
0
0
3
6
9
12
THICKNESS OF COAL BED (feet)

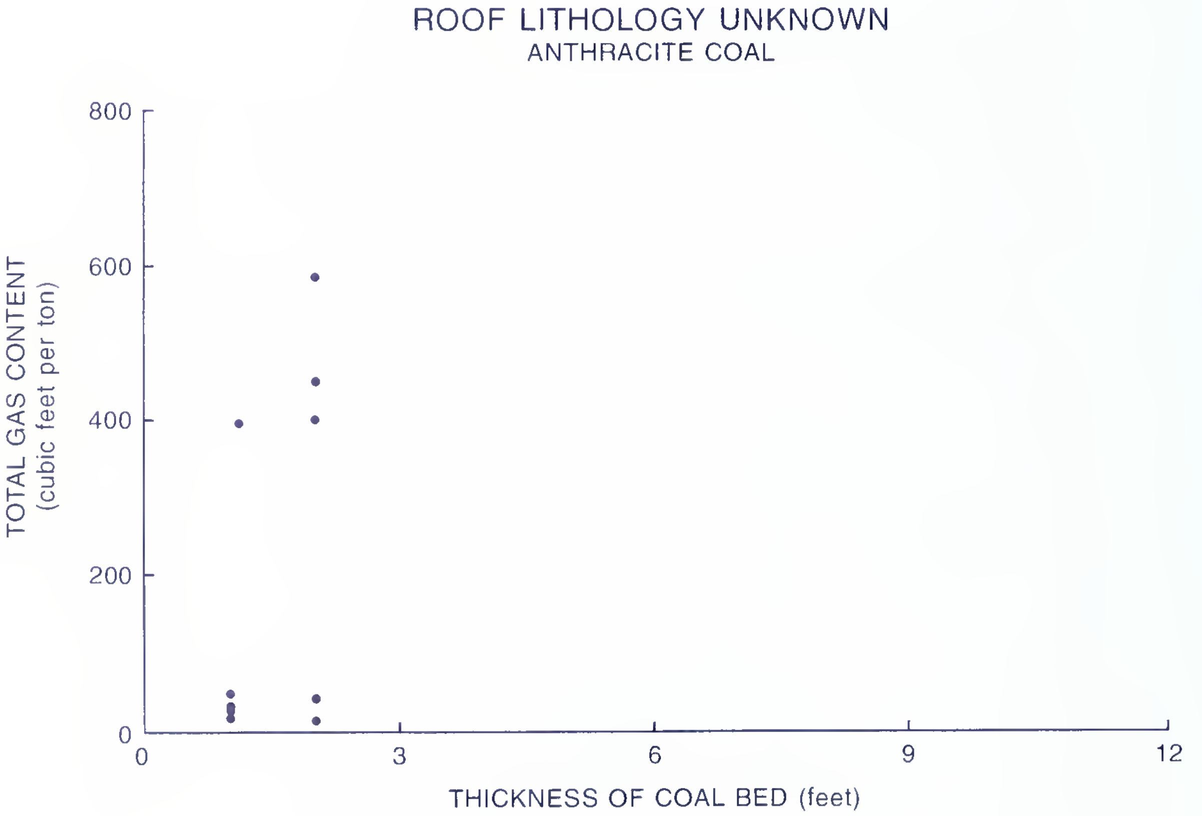

SHALE ROOF
ANTHRACITE COAL
TOTAL GAS CONTENT
(cubic feet per ton)
0
200
400
600
800
0
500
1000
1500
2000
DEPTH TO BASE OF COAL BED (feet)

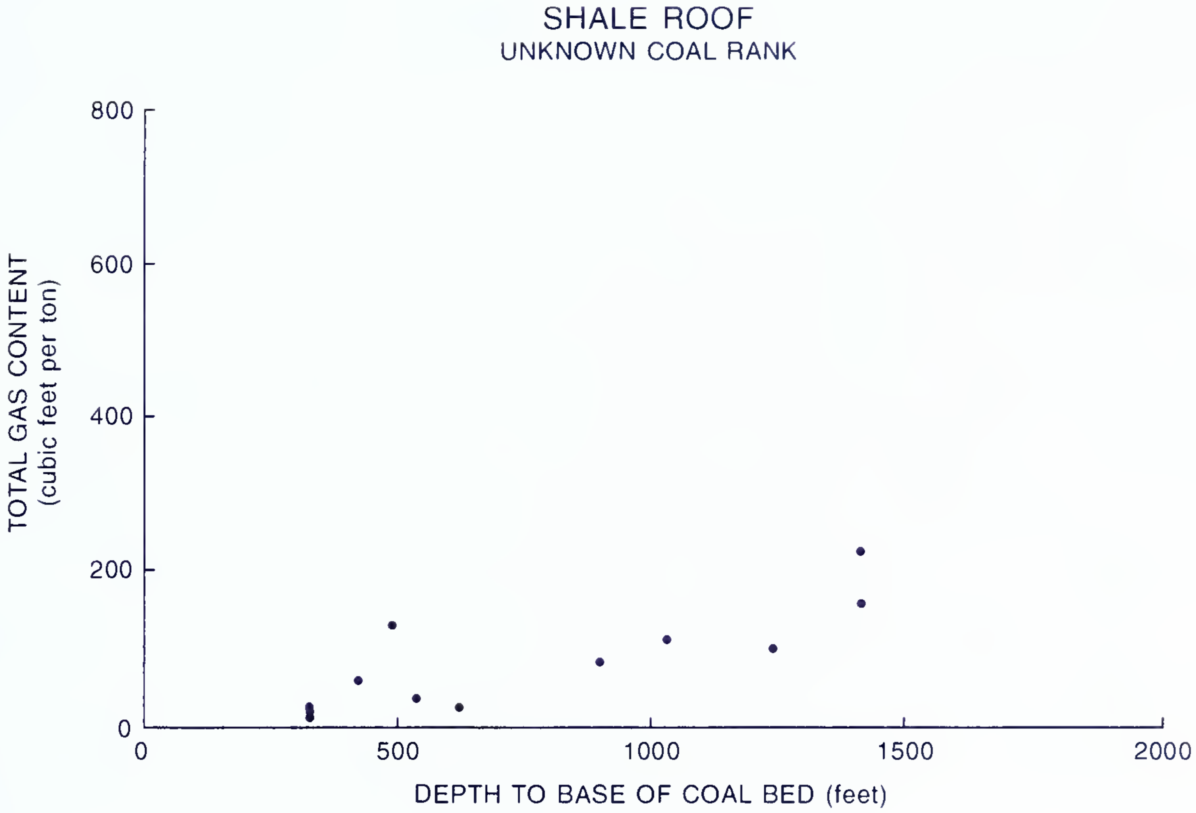

SHALE ROOF
ANTHRACITE COAL
TOTAL GAS CONTENT
(cubic feet per ton)
0
200
400
600
800
0
3
6
9
12
THICKNESS OF COAL BED (feet)

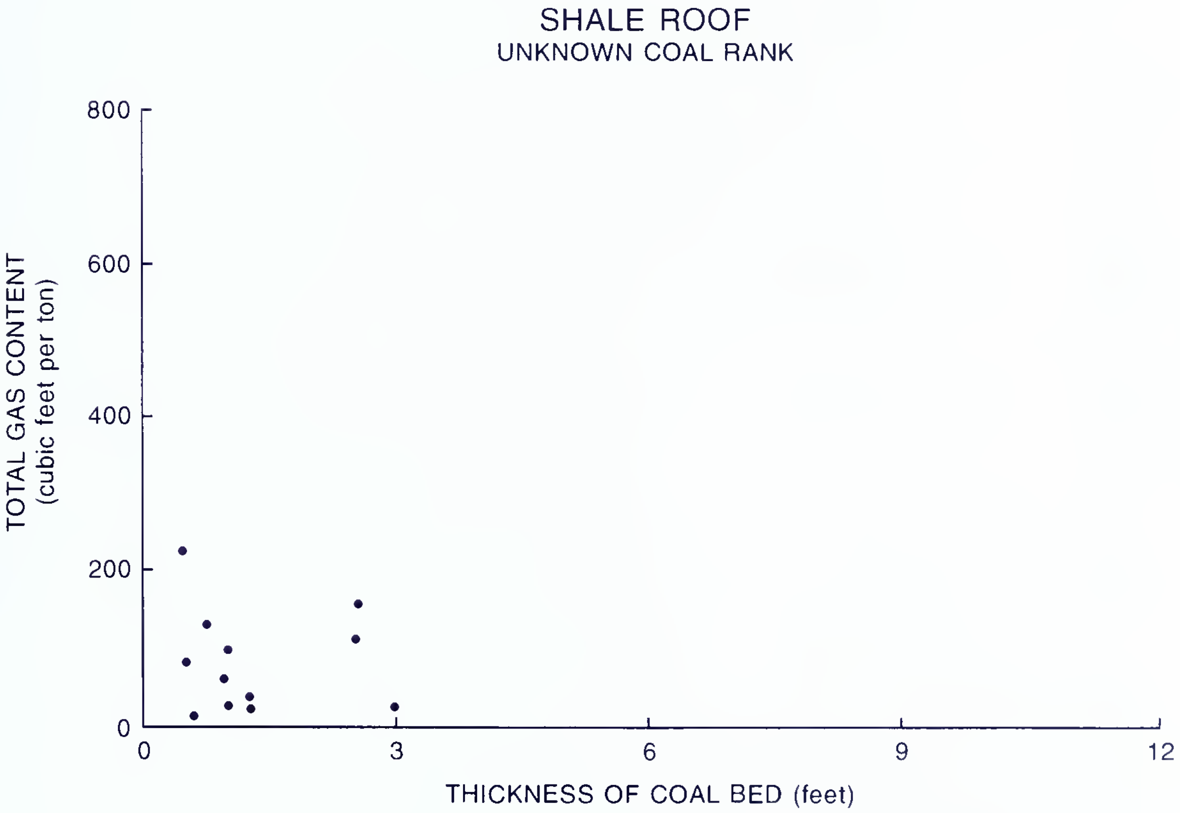


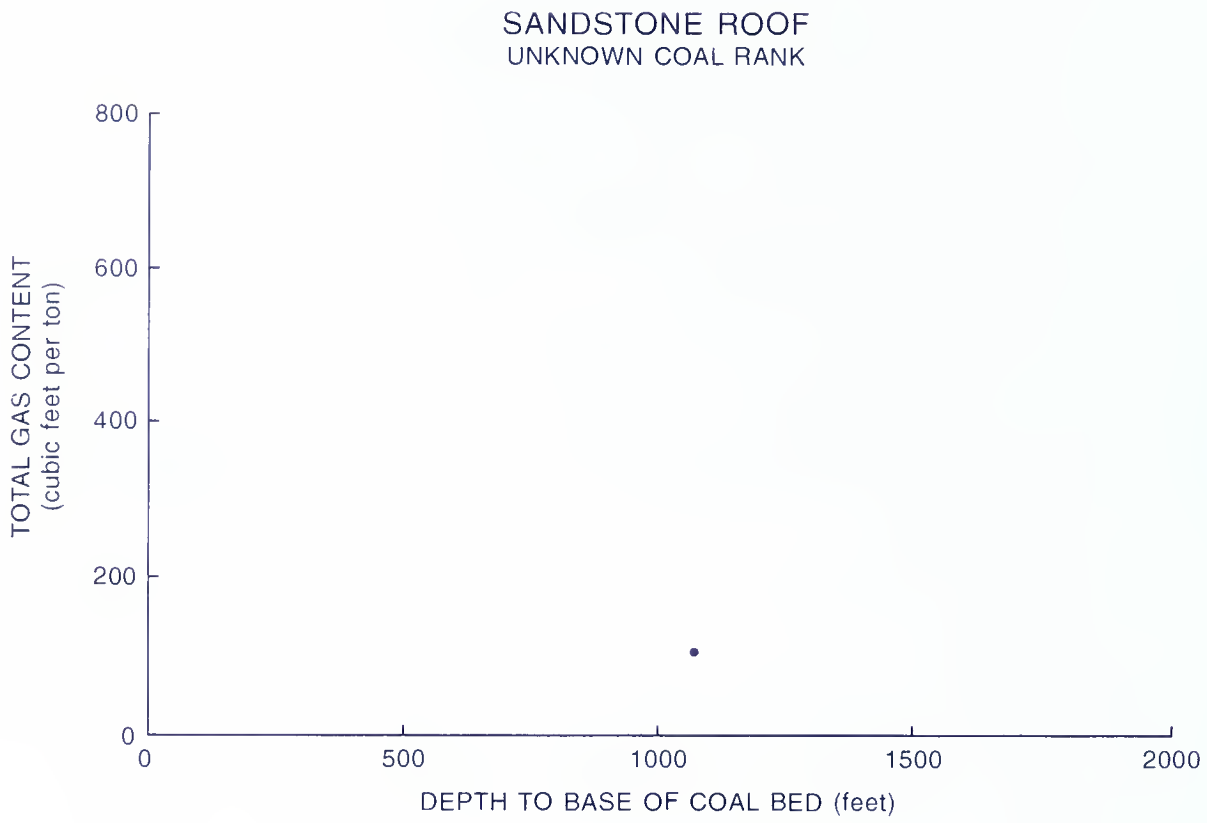
No graph for thickness of coal bed for anthracite coal, mudstone roof lithology.

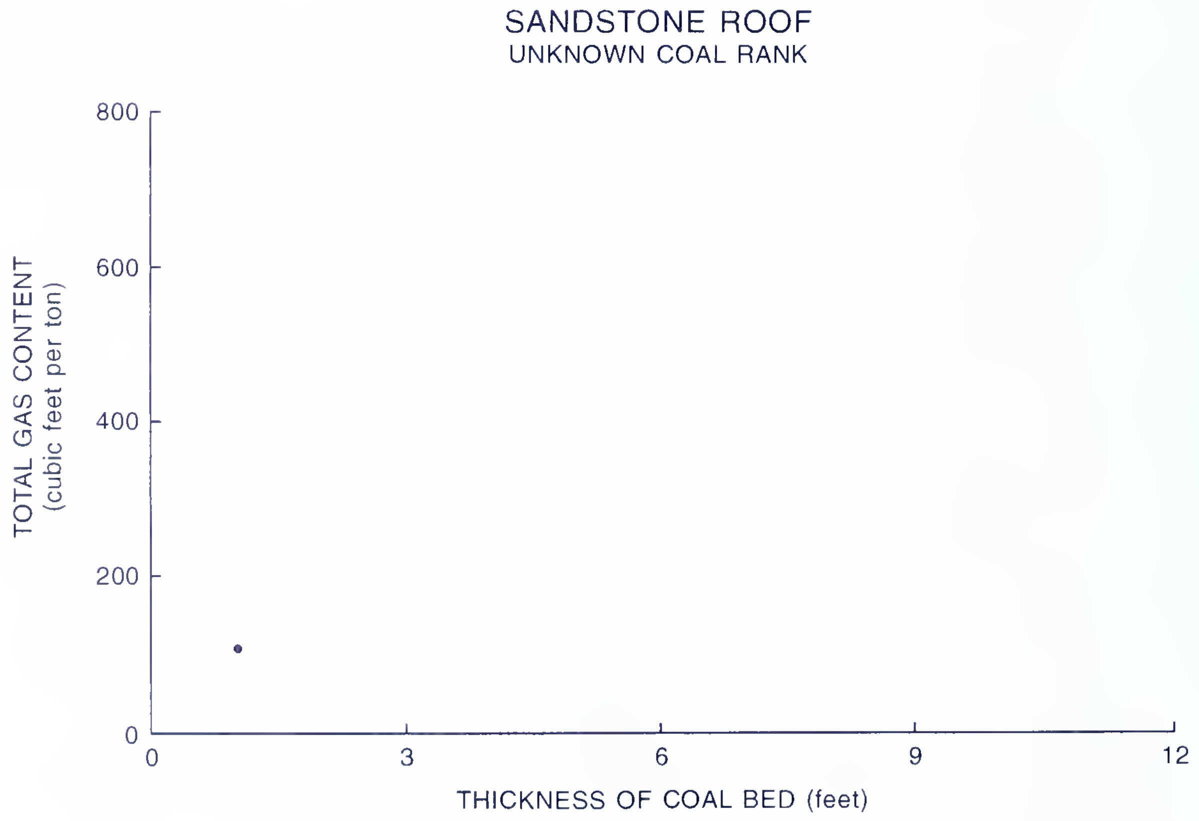

ROOF LITHOLOGY UNKNOWN
ANTHRACITE COAL
TOTAL GAS CONTENT (cubic feet per ton)
0
200
400
600
800
0
500
1000
1500
2000
DEPTH TO BASE OF COAL BED (feet)


ROOF LITHOLOGY UNKNOWN
ANTHRACITE COAL
TOTAL GAS CONTENT (cubic feet per ton)
0
200
400
600
800
0
3
6
9
12
THICKNESS OF COAL BED (feet)


SHALE ROOF
UNKNOWN COAL RANK
TOTAL GAS CONTENT (cubic feet per ton)
800
600
400
200
0
0
500
1000
1500
2000
DEPTH TO BASE OF COAL BED (feet)


SHALE ROOF
UNKNOWN COAL RANK
TOTAL GAS CONTENT (cubic feet per ton)
800
600
400
200
0
0
3
6
9
12
THICKNESS OF COAL BED (feet)


SANDSTONE ROOF
UNKNOWN COAL RANK
TOTAL GAS CONTENT (cubic feet per ton)
800
600
400
200
0
0
500
1000
1500
2000
DEPTH TO BASE OF COAL BED (feet)


SANDSTONE ROOF
UNKNOWN COAL RANK
TOTAL GAS CONTENT (cubic feet per ton)
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3
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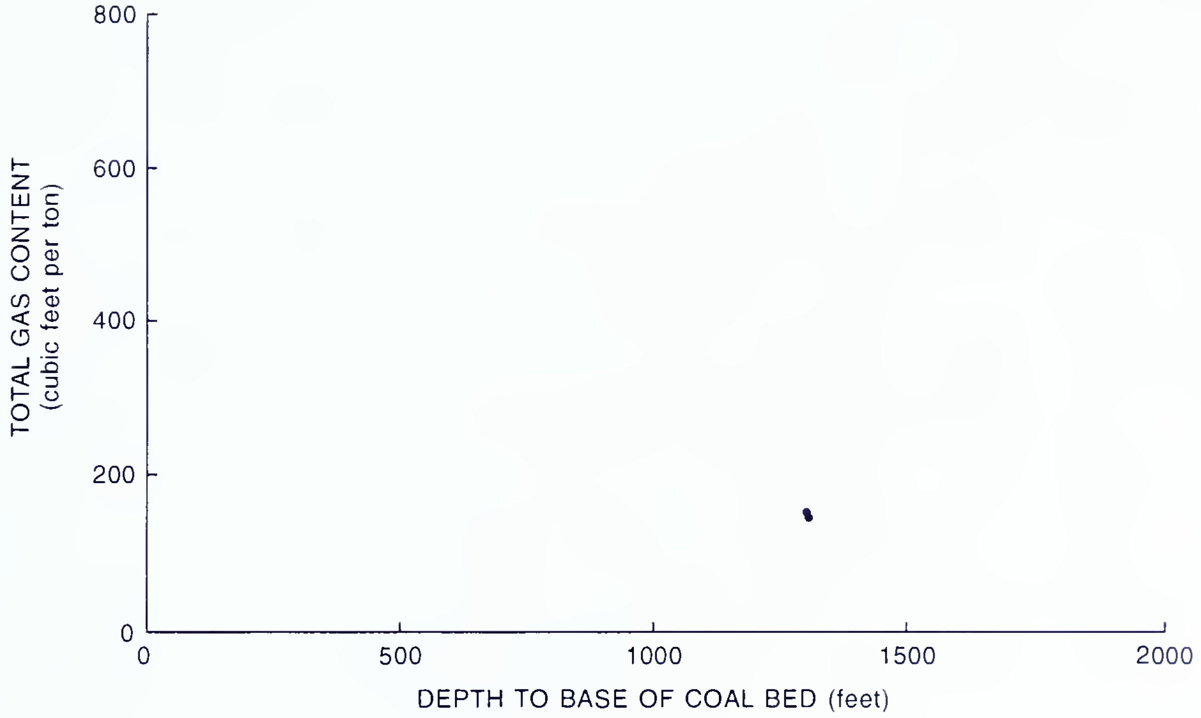
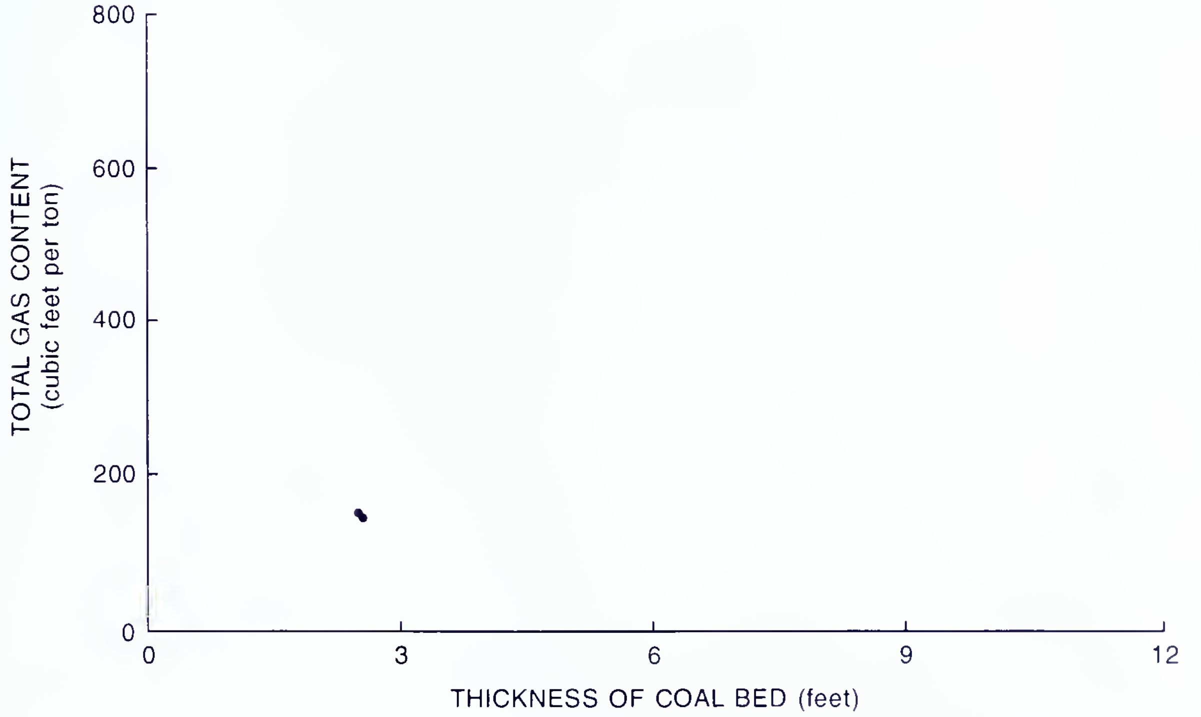


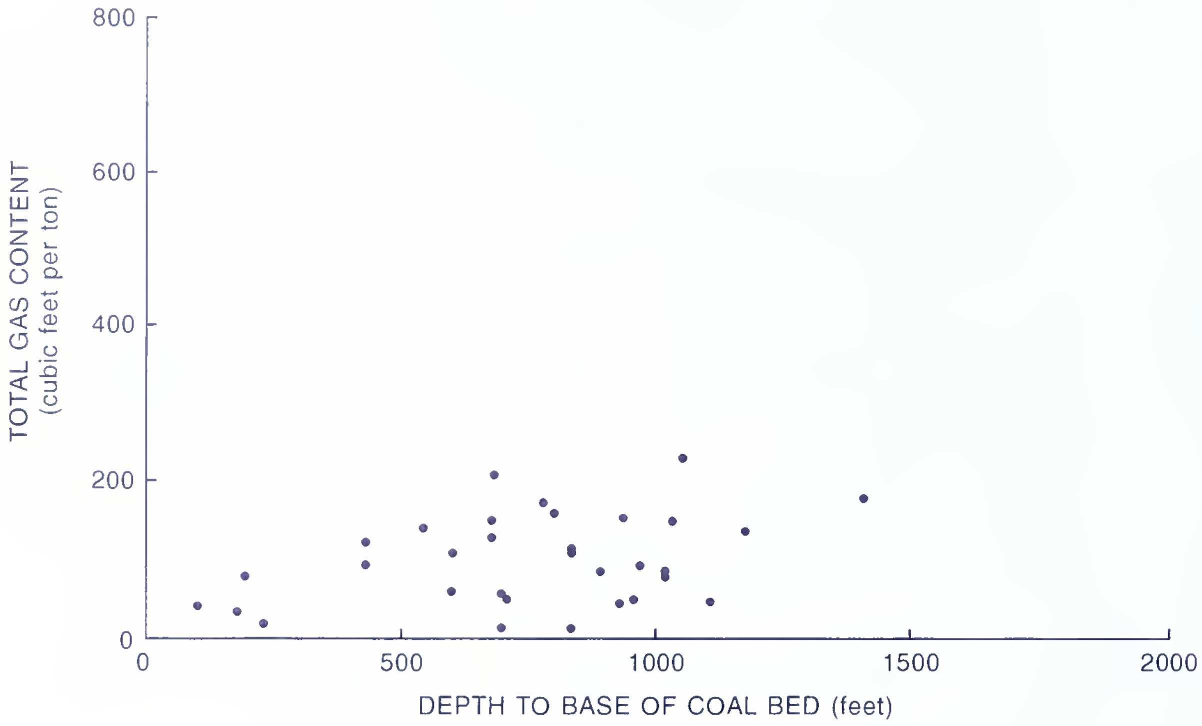
SANDSTONE AND SHALE ROOF
UNKNOWN COAL RANK



SANDSTONE AND SHALE ROOF
UNKNOWN COAL RANK

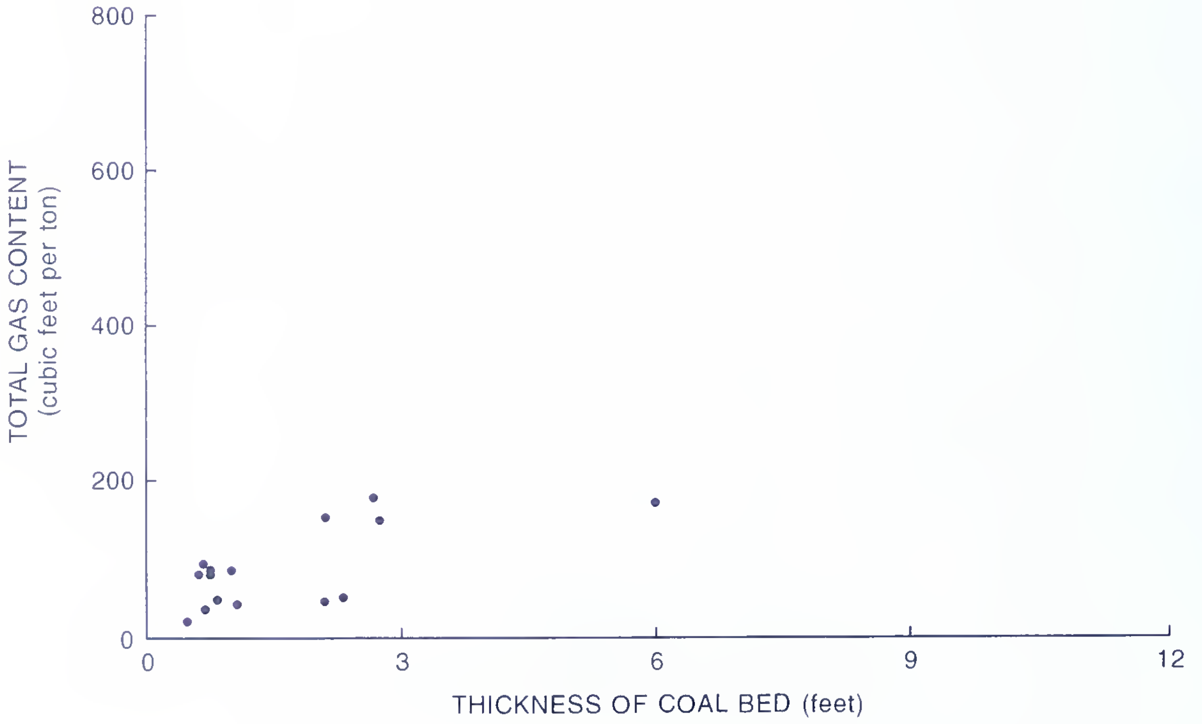
ROOF LITHOLOGY UNKNOWN

UNKNOWN COAL RANK



ROOF LITHOLOGY UNKNOWN

UNKNOWN COAL RANK



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